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DEVELOPMENT OF A STANDARDISED CUP ANEMOMETER SUITED TO WIND ENERGY APPLICATIONS

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DEVELOPMENT OF A STANDARDISED CUP ANEMOMETER SUITED TO WIND ENERGY APPLICATIONS – (CLASSCUP)

Table of contents:

1 Partnership

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2 Abstract

Errors associated with the measurements and interpretation of the measured wind speed are the major sources of uncertainties in power performance testing of wind turbines. Field comparisons of well calibrated anemometers of different types often show significant and not acceptable differences.

The objective were to determine the optimum design for a cup anemometer which should be free from the design faults associated with all of the instruments currently commercially available. The objective were also to prepare a classification system for cup anemometers. which will allow users of anemometry in the wind energy field to rank and select anemometers suited to specific required applications.

The extensive experiments including tests in wind tunnels, of more than 500 anemometer configurations, fields tests and tests in laboratories together with the assessment and modelling work have helped to build up a thorough knowledge of the importance of different design parameters in terms of various behavioural effects. Influenced by trends from the international standardisation work, an early decision was made to focus on a vector, 3D, (angle-insensitive anemometer) cup-anemometer and to focus on conical cups since their sensitivity to vertical velocity components appeared to be less sensitive to the wind speed

The key measures taken to develop the new design consisted of an appropriate selection of the detailed design of the cup geometry's and mounting the cups at appropriate radius on a slender symmetric body. The development finally ended with an anemometer that gave a very good flat response within 1% over the range from –45º to +35º and had a good linear calibration curve. Four prototypes of the anemometer optimised for flat response were produced. The flat response was also confirmed by field tests over the range ±20°. A patent application of the new anemometer was filed on the 6:th of October 2000.

By the time the project was initiated there was a general consensus that overspeeding errors in indicated mean wind speed were very low. Extensive experiments with anemometers exposed to fluctuating wind and measurement of driving torque have shown that anemometers of different design can have very different tendencies to overspeed. Some anemometers can have a high tendency to overspeed and some can even have a tendency to underspeed. It was found that the very detailed shape of the torque versus speed ratio characteristics, especially near the equilibrium speed ratio, is of vital importance for the performance of cup anemometers operating in turbulent conditions.

A classification method for cup anemometers has been developed. General external operational conditions have been proposed. A normal category range connected to ideal sites of the IEC power performance standard was made, and another extended category range for complex terrain was proposed. General classification indices were proposed for all types of cup anemometers. As a result of the classification, the cup anemometer will be assigned to a certain class: 0.5, 1, 2, 3 or 5 with corresponding intrinsic errors (%) as a vector instrument (3D) or as a horizontal instrument (2D).

The classification of three commercial cup anemometers showed that for the normal category the best class for horizontal wind speed measurements was class 2 and for vector measurements class 3. The Classcup prototype anemometer got class 2 as a horizontal anemometer and class 1 as a vector anemometer. For the extended category the commercial cup anemometers were class 5 for either horizontal or vector measurements, whereas the Classcup anemometer got class 3 as a vector instrument.

By using the new-designed Classcup anemometer the accuracy of vector wind speed measurements can therefore be significantly improved.

3 Objectives

Errors associated with the measurements and interpretation of the measured wind speed are the major sources of uncertainties in testing and evaluation of wind turbines. The improvement of calibration techniques during the last few years was hoped to bring the uncertainties below acceptable levels. However, field comparisons of well-calibrated anemometers still show a significant and not acceptable difference.

The primary objective of the project was to produce an optimal design for a standardised, cup anemometer, which is suited to the requirements of the wind turbine industry, applicable for a relevant range of wind speeds, turbulence intensities, slopes, air densities and air temperatures. The design shall be essentially free from the design faults: no definition of what they measures; bad angular characteristics; high sensitivity to friction in bearings; no documented sensitivity to dynamics, which are associated with all of the instruments currently commercially available.

A secondary objective was to prepare a classification system, which will allow users of anemometry in the wind energy field to select anemometers suited to specific required applications. For known ranges of environmental operational conditions, for wind turbines and cup anemometers, the user of the system shall be able to assess the accuracy of cup anemometers, and to compare different designs.

Another secondary objective was to verify the physics behind the angular characteristics using flow visualisation techniques.

4 Research Approach and Methodology

The approach of the project has been largely experimental with a very clear practical objective. Computer based or analytical modelling has only been undertaken to support the experimental work.

The project have involved technical investigations in the areas of:

- sensitivity of cup anemometers to wind speed components outwith the horizontal plane
- bearing friction, with particular regard to temperature effects
- dynamic response and its effect on the accuracy of mean wind speed and turbulence measurements

These investigations has been used in the context of two main target deliverables, these being

- a new classification scheme for cup anemometers
- a new, high accuracy, standard design for a cup anemometer suited to wind energy applications

An understanding of the importance of different design parameters in terms of various behavioural effects has been built up.

The parameters include:

- cup and rotor geometry
- body and shaft cover geometry
- design and characteristics of bearings

5 Technical Description

5.1 Wind Tunnel Studies, Assessments and Optimisations

Extensive tests have been carried out in four wind tunnels to determine how various geometric parameters affect the sensitivity of cup anemometers to out-of-plane wind speed components. More than 500 different anemometer configurations have been tested.

In the following selected graphs are presented to exemplify what has been accomplished.

5.1.1 Vertical sensitivity tests in wind tunnel L2000 at KTH

The objective was to investigate different methods of testing such as turning the turntable slowly with the anemometer in the centre of the tunnel (α-sweep) or moving the tilt device slowly back and forth in the centre of the tunnel (β-sweep).

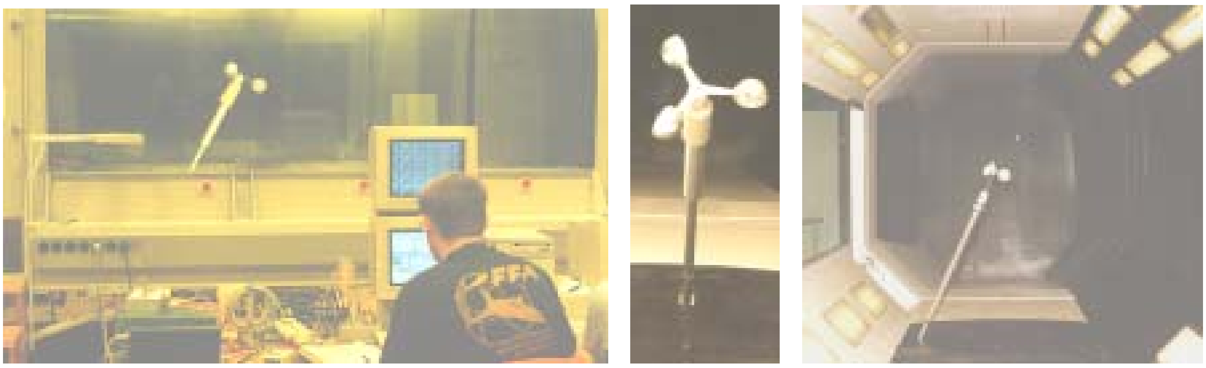

Figure 1a, b&c, Pictures from tests with the Thies anemometer (β-sweep) and a view from the L2000 wind tunnel with α-sweep tests with the Risø anemometer.

The object was also to test the commercial anemometers used by the project partners, the Vaisala, the Thies and the Risø anemometers.

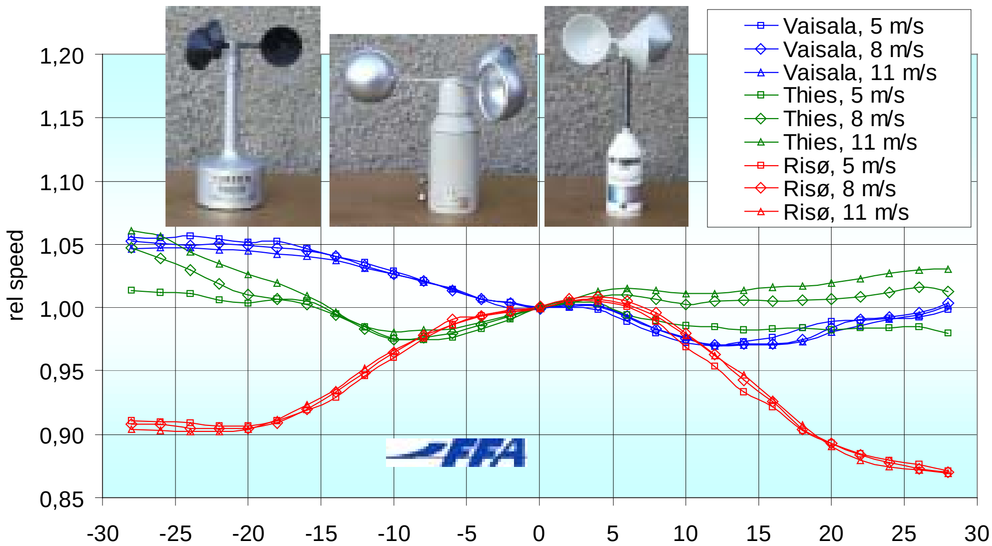

Figure 2, Sensitivity for inflow angle and wind speed for the Vaisala, the Thies and the Risø anemometers.

Conclusions from the first test in wind tunnel:

- Longer measuring time implies smoother curves.
- Similar results were obtained for β- and α-sweep tests.
- α-sweep tests give an undesired concentration of data points at the ends.
- Vaisala and Risø have distinctly different responses for negative inflow angles (from below), in spite of the fact that both anemometers have conical cups.
- Thies, with spherical cups seems to be the most sensitive to wind speed.
- Minor modifications of the shape of the cups lead to clear effects.

5.1.2 Influence of Geometrical Parameters in the Vertical Sensitivity of Experimental Cup Anemometers-Studies by DEWI

Previous investigations with regard to the sensitivity-to-tilt angle often showed completely different anemometer behaviour, although the cups of the instruments tested were quite similar. This contradictory behaviour was investigated in the wind tunnel laboratory. For this purpose an anemometer was designed which allowed the change of cups. Hemispherical and conical cups with different shaft lengths and angles were tested.

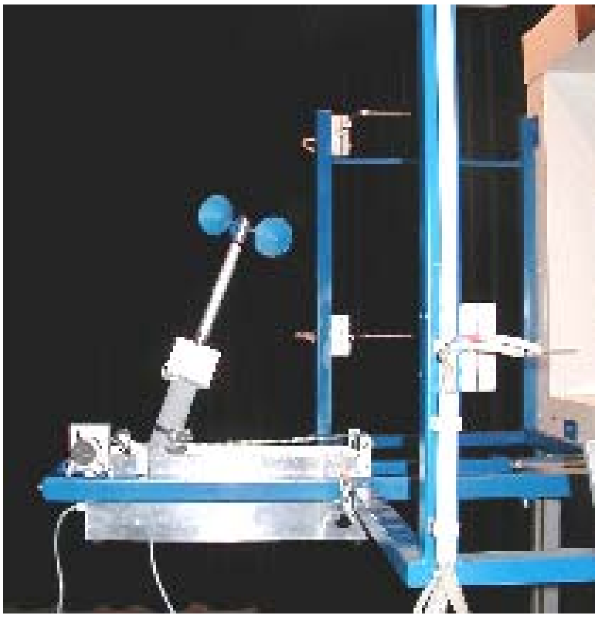

Figure 3, Wind tunnel outlet with the tilt device that always keeps the anemometer in the same position within the measuring sector.

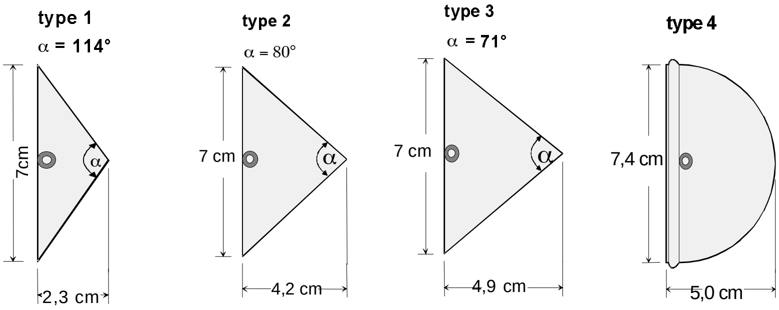

Figure 4, Dimensions of experimental cups

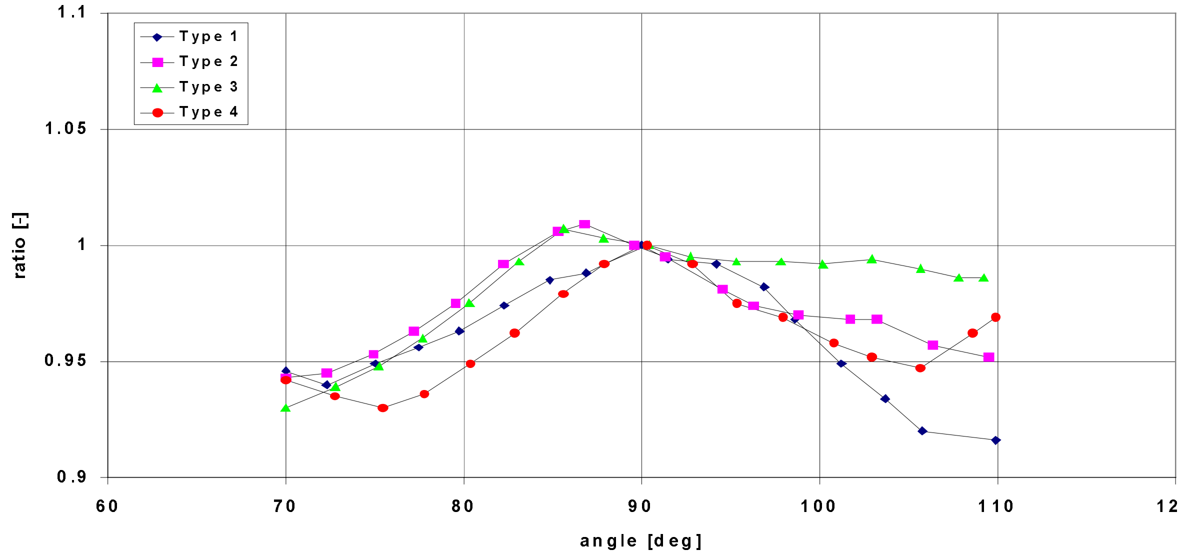

Figure 5, Influence on vertical sensitivity due to different cup shapes (cup type 1-4; distance cup centre to centre of rotation approx. 6.5 cm, wind speed approx. 12 m/s).

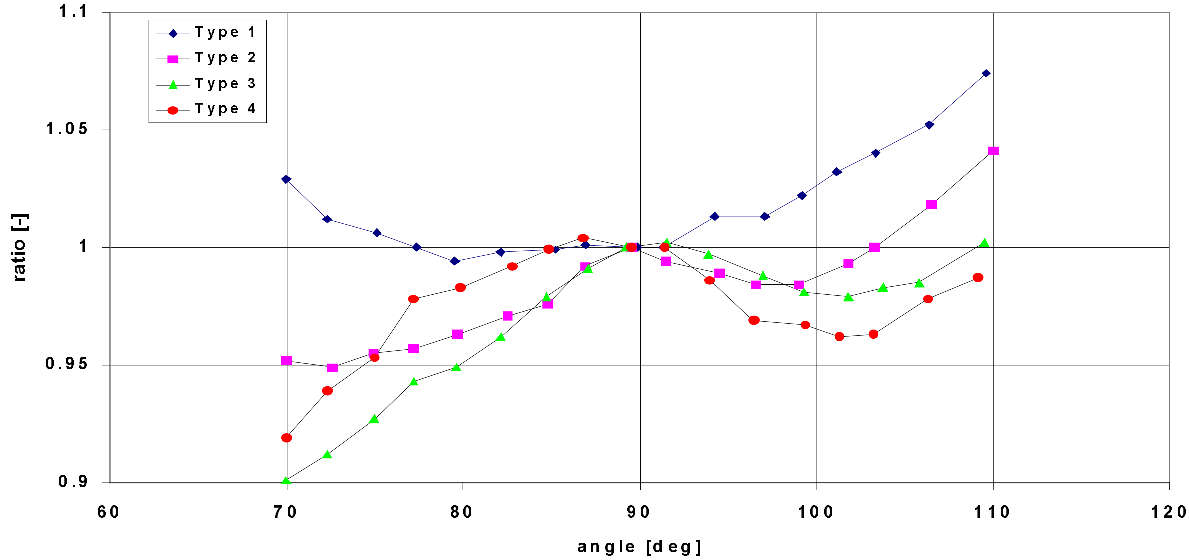

Figure 6, Influence on vertical sensitivity due to different cup shapes (cup type 1-4; distance cup centre to centre of rotation approx. 10 cm, wind speed approx. 12 m/s).

5.1.2.1 Conclusions

- A strong influence of the rotor radius was found
- Only the hemispherical cup showed a significant wind speed dependence
- The conical cups with an angle of 114° had a stronger influence than the other conical cups
- The shape of the body and the length of the neck have a strong influence

5.1.3 Smoke Visualisations

One way of studying the flow field around an anemometer in action is smoke visualisations and this was one of the methods chosen in this project. In the experiments that were carried out in the low-velocity smoke-tunnel at FFA, single cups as well as complete anemometers were tested. A few samples of complete rotors are shown below. The result is a qualitative understanding of which details affects their sensitivity to out-of-plane velocities.

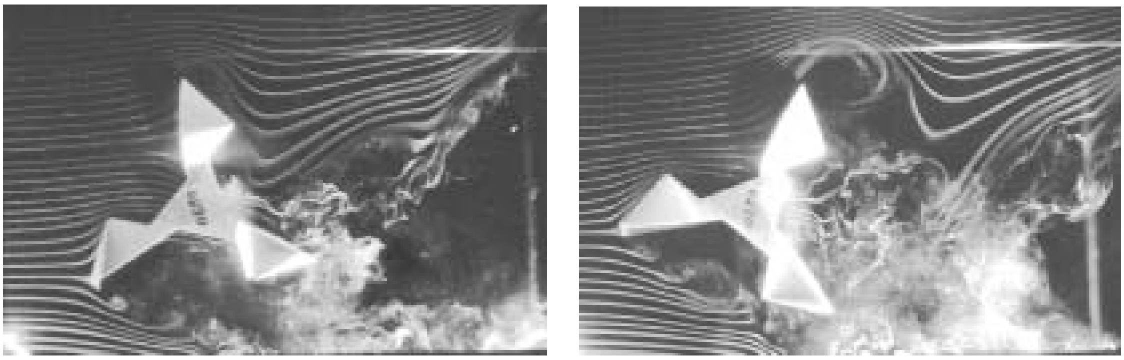

Figure 7a&b, Flow pattern around a Risoe rotor

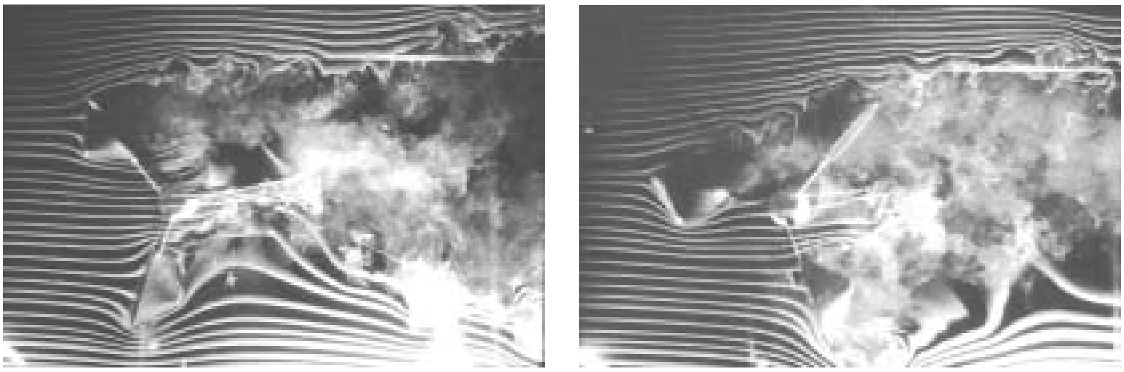

Figure 8a&b, Flow pattern around a Vaisala rotor

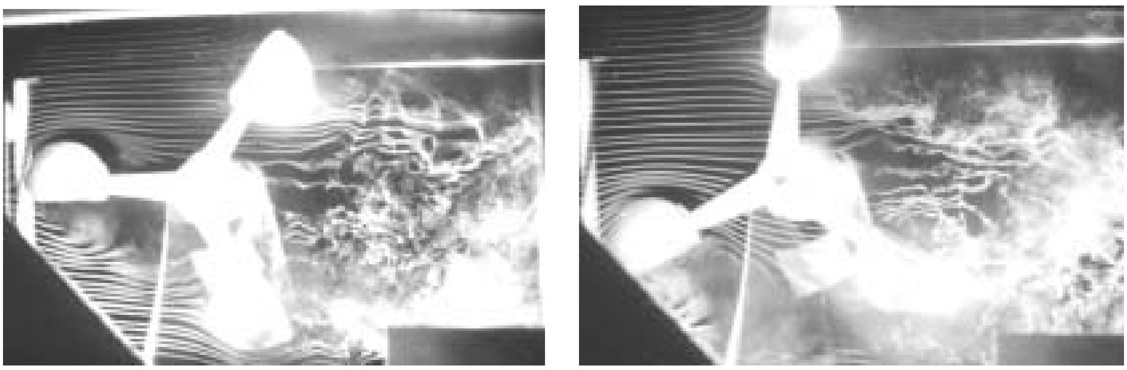

Figure 9a&b, Flow pattern around a Thies rotor

- The wakes behind single cups shrink smoothly in the down-stream direction while the wakes behind the cups of an anemometer interact and form an irregular, growing global wake.

5.1.4 Vertical Sensitivity Tests in FFA-LT5

The experiments were conducted in the LT-5 open-circuit, NPL-type wind tunnel at the Aeronautical Research Institute of Sweden. This tunnel has a cross-section of 0.9x 0.675 m and a velocity range of 5-16 m/s, Figure 10.

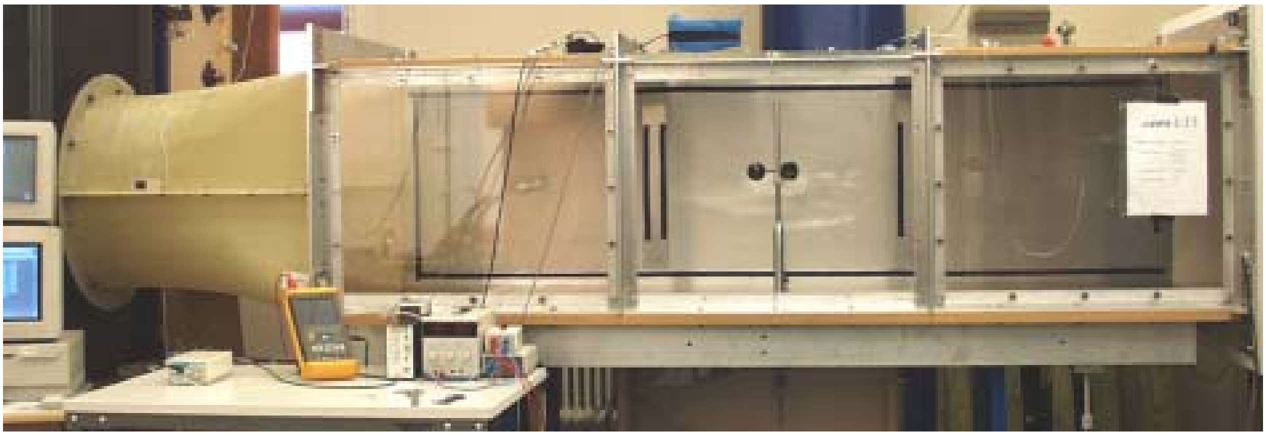

Figure 10, The LT5 wind tunnel at FFA, where most of the wt-tests were carried out.

Figure 11a, b & c, The tilt device in LT5

To investigate the vertical sensitivity the test object is mounted on a pole located in the centre of the tunnel. In order to have a symmetric arrangement the 15 mm pole was made up of three parts. The lower fixed part, the middle rotating part and the upper fixed part. The middle part, the hub, was equipped with holes to fix cup arms.

In addition to the conventional conical and hemispherical cups, a few novel designs were examined. These consisted of tetrahedral, half-cylindrical and crescent-shaped cups. The new cup designs seemed in no way inferior to the traditional designs, even though the limited time available made it impossible to optimise their shape, size and rotor diameters.

Below graphs of angular response curves for commercial anemometers are shown.

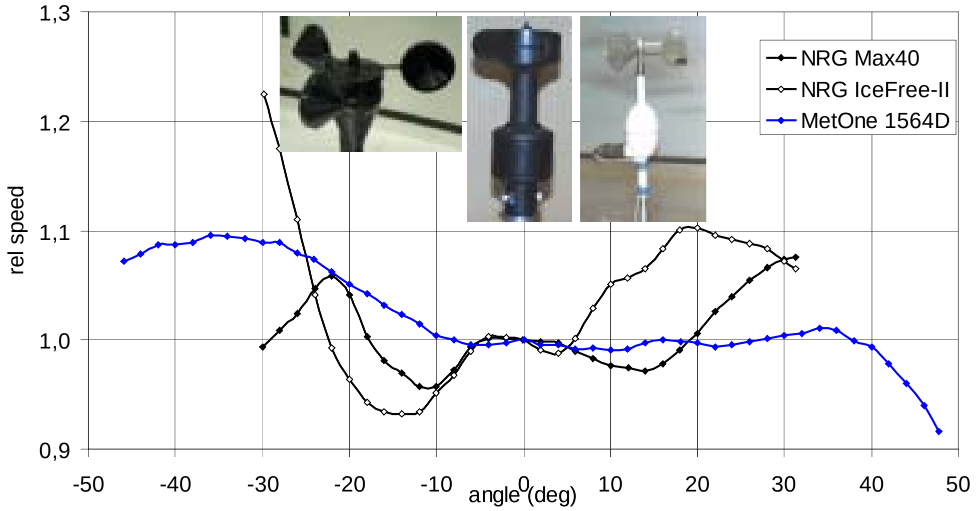

Figure 12, Vertical sensitivity tests for NRG Max 40, NRG IceFree & MetOne at 8 m/s

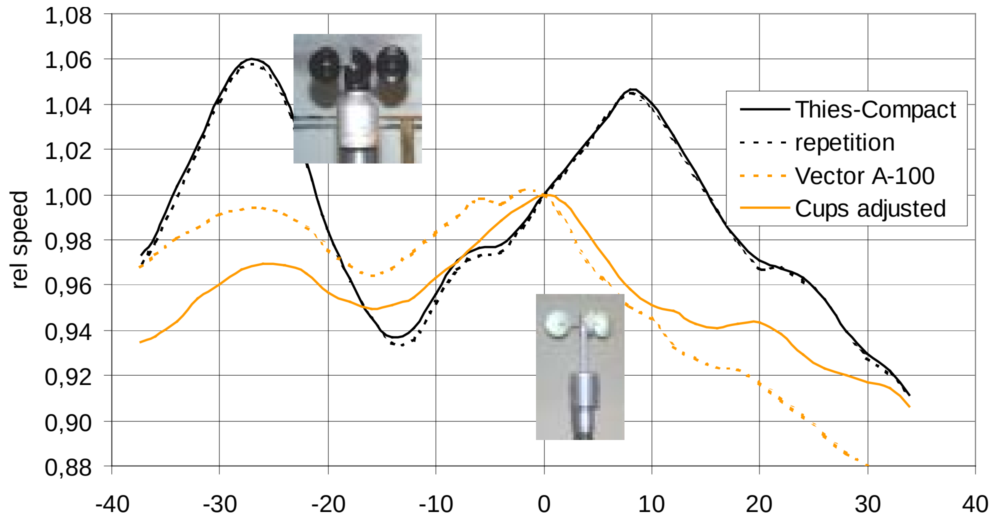

Figure 13, Vertical sensitivity tests for Thies-Compact & Vector A-100 at 8 m/s

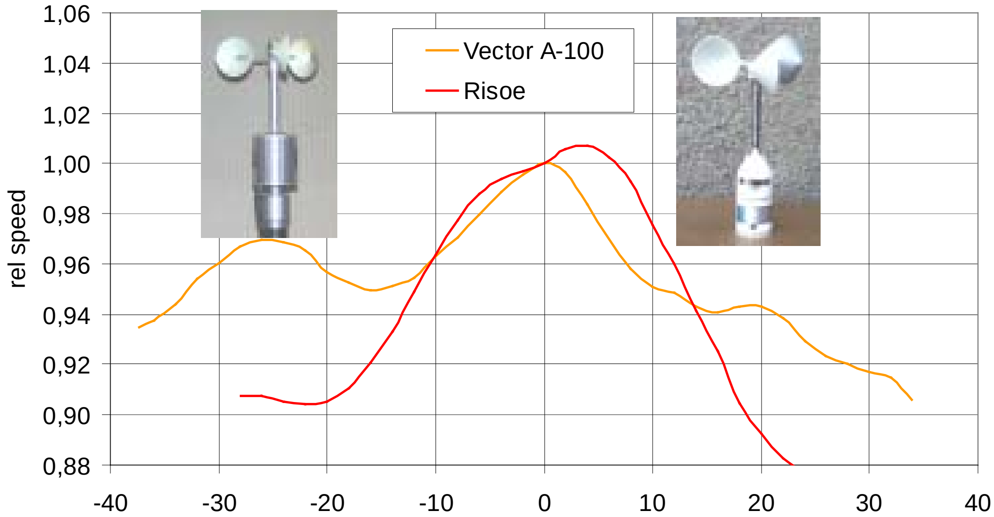

Figure 14, Vertical sensitivity tests for Vector A-100 and Risoe at 8 m/s

Below selected graphs of the different cup designs and the characteristics of their tilt angle response curves will be presented. The presented results represent only a small fraction of all results.

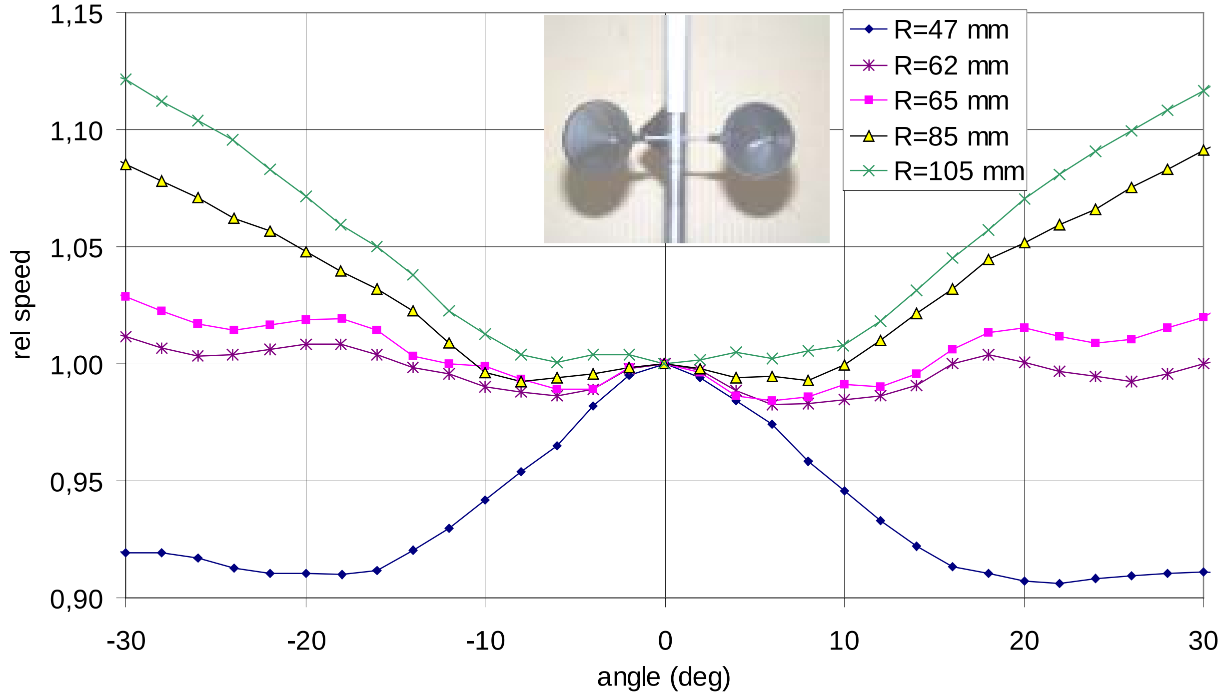

Figure 15, Influence of arm radius for Vaisala cups at 8 m/s

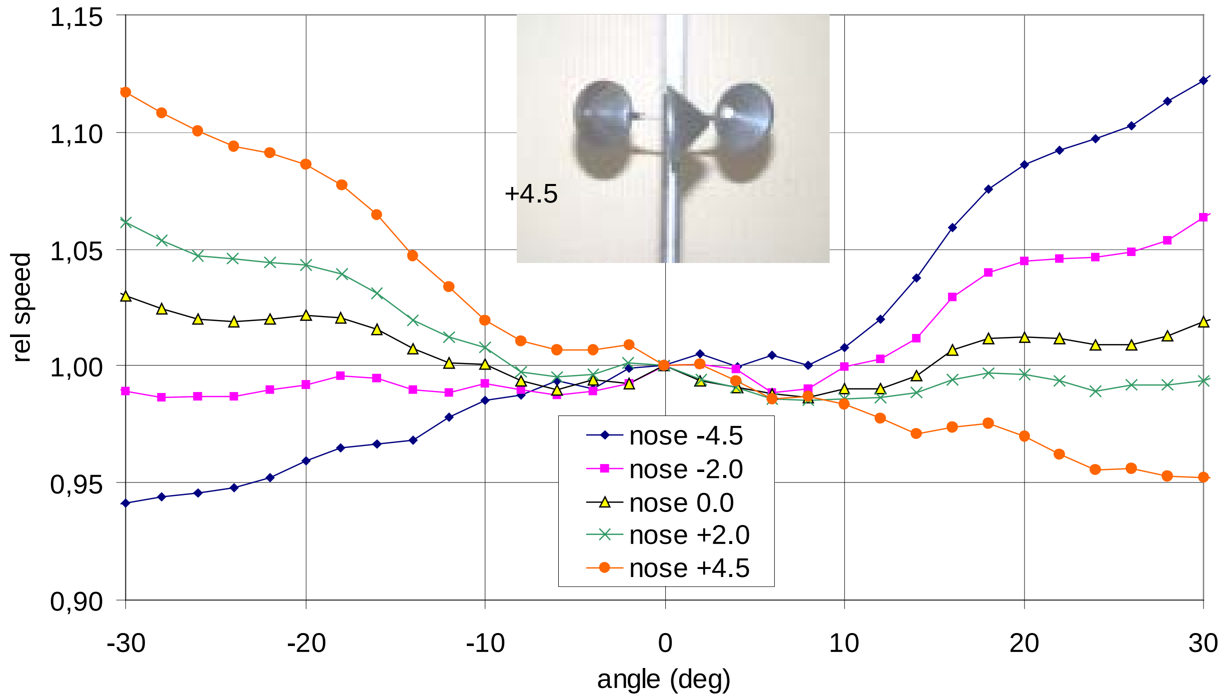

Figure 16, Influence of cup angle for Vaisala cups at 8 m/s

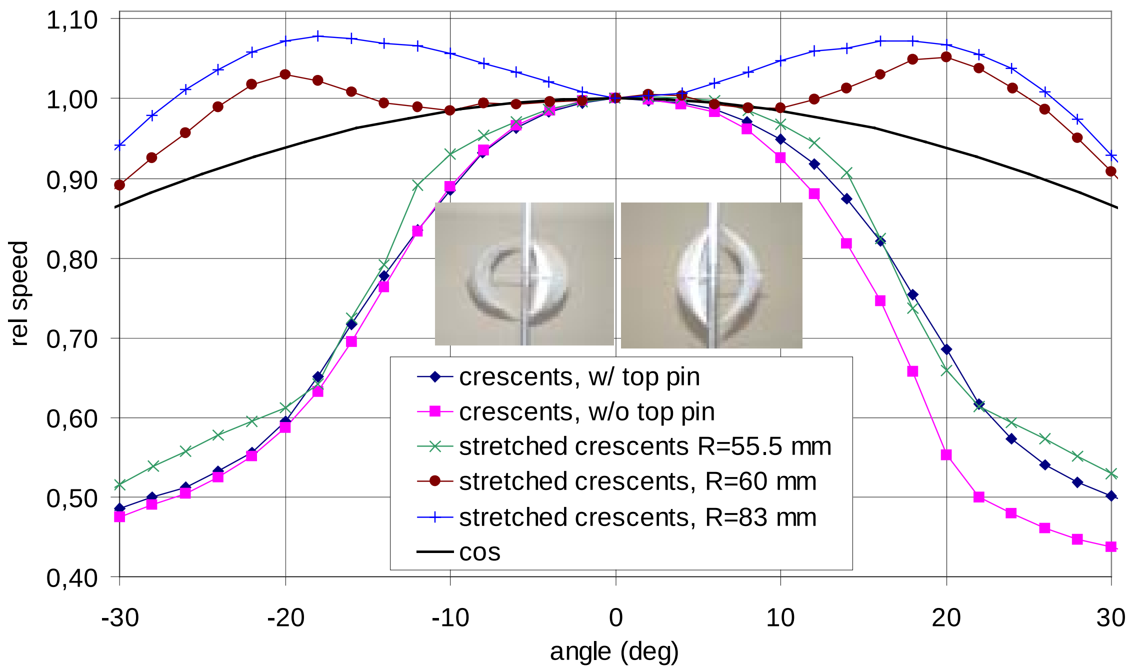

Figure 17, Influence of vertical sensitivity for crescent-shaped cups

5.1.4.1 Observations from the studies of commercial anemometers in LT5

A number of commercial anemometers and novel anemometer designs have been tested. In the tests, the angular sensitivity of the anemometers over the –30 - +30° range and sometimes over the –45 - +45° range has been examined at 8 m/s. A few tests have also been made at other free-stream velocities. As can be seen in the graphs the sensitivity for vertical wind components is in general very high. No commercial anemometer succeeds to stay within ±5% limits for inflow angles in the –30 - +30° range, regarding them as vector instruments.

5.1.4.2 Observations from the parameter studies in LT5

It was found that one of the most important factors in determining the response function of an anemometer is its cup-to-rotor size quota. The farther away from the axis the cups are located, the more the anemometer tends to give high relative speeds at high angles of attack.

A slight tilting of the cups in the vertical direction made the response curves highly asymmetric, even for out-of-plane angles of only 2°. This feature is thought to offer a way to counteract other asymmetries arising from the geometry of the anemometer.

Covering the conical cups from Vaisala and Risø was also tried. This gave somewhat different response curves, including a near-cosine curve using covered Risø cups.

The effects of hub/shaft and house diameter were examined (not shown here) using cylinders that could be placed on the hub/shaft. It was found that as long as they are kept some distance away from the anemometer rotor, the influence of the shaft is rather small. On the other hand, the design of the shaft/hub near the rotor is of vital importance for the response curves.

Three new design concepts were tested. Half-cylindrical cups between two discs had a very flat response for small angles, but retarded for higher angles. Tetrahedral cups had response curves similar to the conical cups, but a “dip” in the relative speed occurs at 12° rather than at around 7° and there is some extra acceleration at high angles.

5.1.5 Development of the Classcup anemometer

The final steps in the development of an optimum design were to decide on the type of cup anemometer, and to use the broad technical knowledge gained in the project. The project team made the following decisions:

- focus on the search for a flat responding anemometer.
- focus on the detailed design of the conical cups since their vertical sensitivity appeared to be less sensitive to wind speed.

The investigations focused on reshaping the RISØ cups, of which a large number was available. The key measures taken to develop the new anemometer were:

- Selecting conical cups with triangular opening and round corners.
- Mounting the cups on appropriate radius.
- Using a long slender neck and a small house.
- Using an extension (top pin) of the slender axis/neck above the rotor to achieve symmetry.
- Putting plates inside the cups to reduce the high speed for inflow angles < -30° and > 30°
- Trimming the outer edge of the cups to fine adjust the speed over the range from -10° to 0°.
- Trimming the upper edge of the cups to fine adjust the speed over the range from 0° to 30°.
- Fine adjusting the cup angle to reduce the slope and make the angular response symmetric.

This optimisation process finally ended with an anemometer that gave a very good flat response within 1% over the range from –45º to +35º.

A patent application was filed to the Swedish Patent and Registration Office on the 6:th of October 2000.

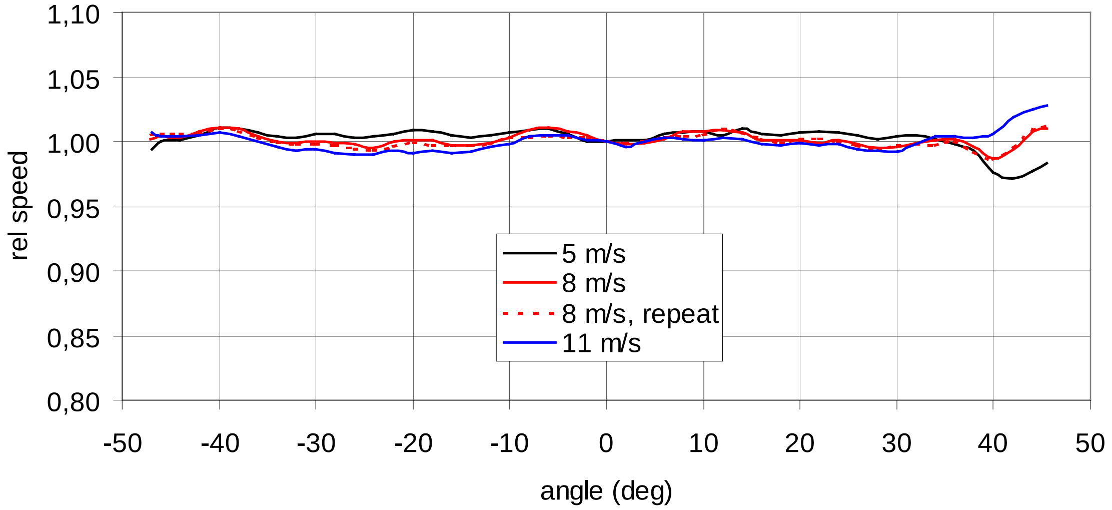

Figure 18, Influence of Wind Speed on Vertical Sensitivity for the Classcup Anemometer

Four anemometer prototypes were manufactured, based on the bearing design of the RISØ cup anemometer. Two were used for the field tests by Dewi, one was used for tests by RISØ and the fourth was used for further studies of dynamic effects by FFA. Figure 19 shows the four prototype cup anemometers.

Figure 19, Four prototypes of the optimised cup anemometer

Figure 20 shows the result from calibration of the Classcup anemometer.

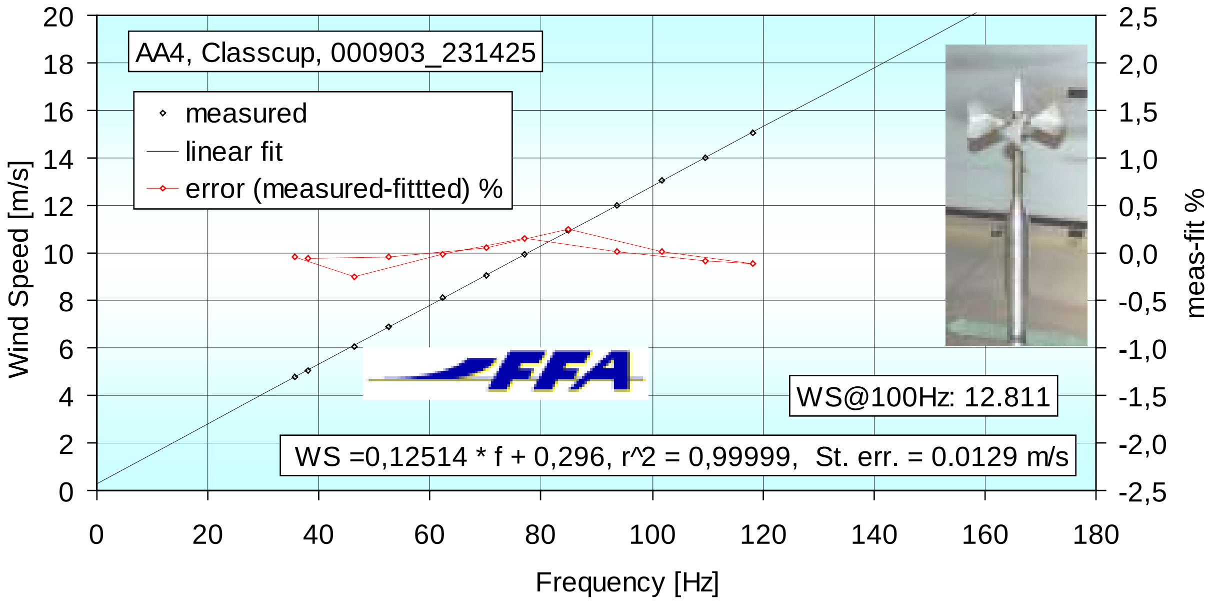

Figure 20, Calibration of Classcup anemometer AA4 in FFA-LT5

5.1.6 Torque measurements

In order to improve the understanding of the effects that determine the behaviour of a cup anemometer, torque measurements that show the detailed pattern of the driving aerodynamic torque on an anemometer cup during one lap were considered to be very valuable.

To make the measurements, the same experimental equipment as in the tilting sensitivity tests was used with the addition of a couple of new tools tailor-made for the torque measurements. The additions to the set-up consisted of a motor with a transmission that could rotate the anemometer axis from 2 rad/s up to significantly faster than its normal operating speed at 8 m/s.

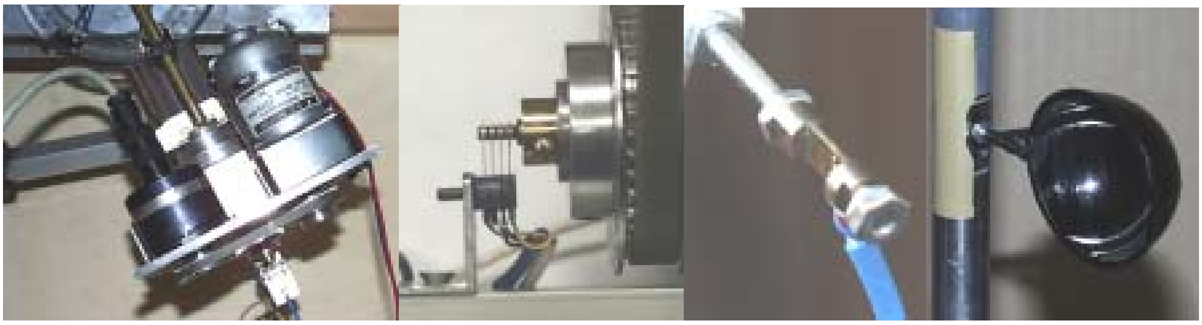

Figure 21, The wind tunnel and the anemometer rotational motor with its transmission and angle potentiometer mounted underneath the test section The slip rings, torque transducer and a mounted single Thies-Compact cup

Static measurements were obtained when the electric motor driving the anemometer was run at its minimal speed, which was about 2 rad/s

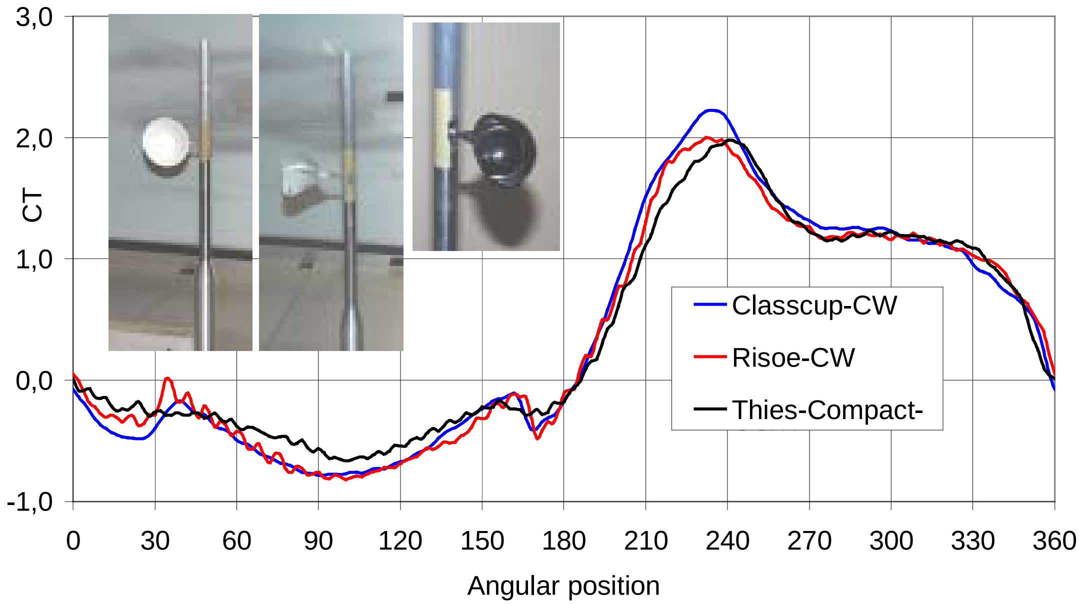

Figure 22, Normalised static torque coefficient C_q. Angular position 0° is when the arm is pointing down wind.

The quality of the torque measurements offered the possibility to measure the off-equilibrium torque characteristics. Once the dynamic response of an anemometer to disturbances is known, the over-speeding of an anemometer in fluctuating wind can be determined.

The measurements were conducted such that a range of tip speed ratios were covered by either keeping the rotational speed fixed and vary the wind speed over a large range or vice versa. The normalised torque coefficient Cq from all combinations of wind speed and rotational speed are shown in Figure 23. The solid curves are fitted 9:th order polynomial. In order to highlight the difference between the three studied anemometers the 9:th order polynomial as in Figure 23 are plotted versus normalised speed ratio in Figure 24. The normalised speed ratio to use are derived from the poly fit which gives zero torque.

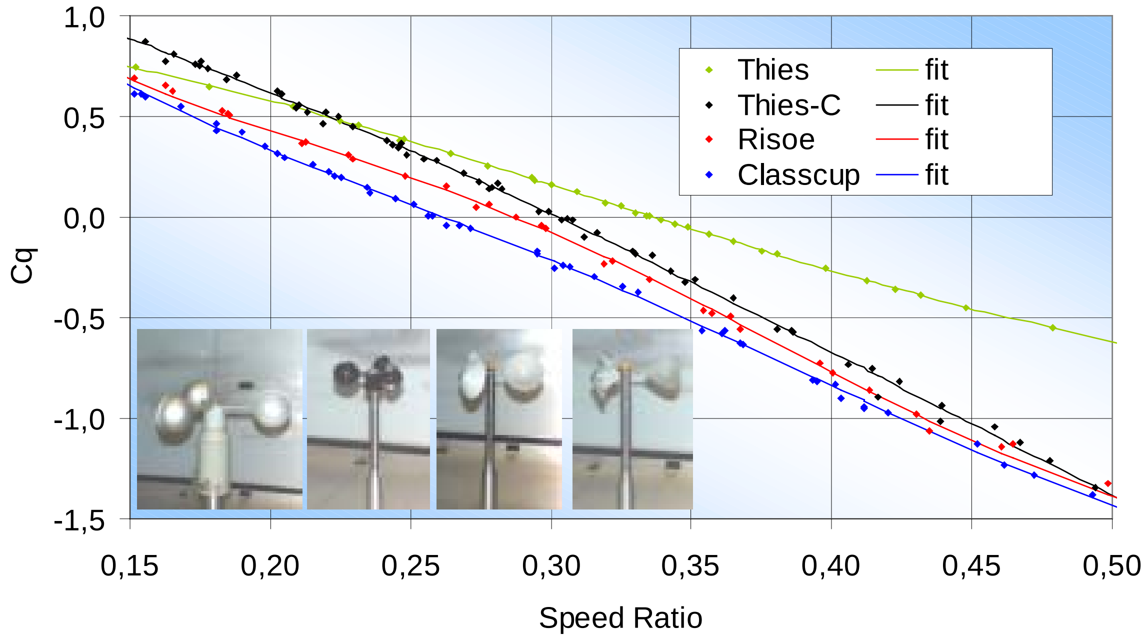

Figure 23, Normalised Torque coefficient vs. Speed Ratio

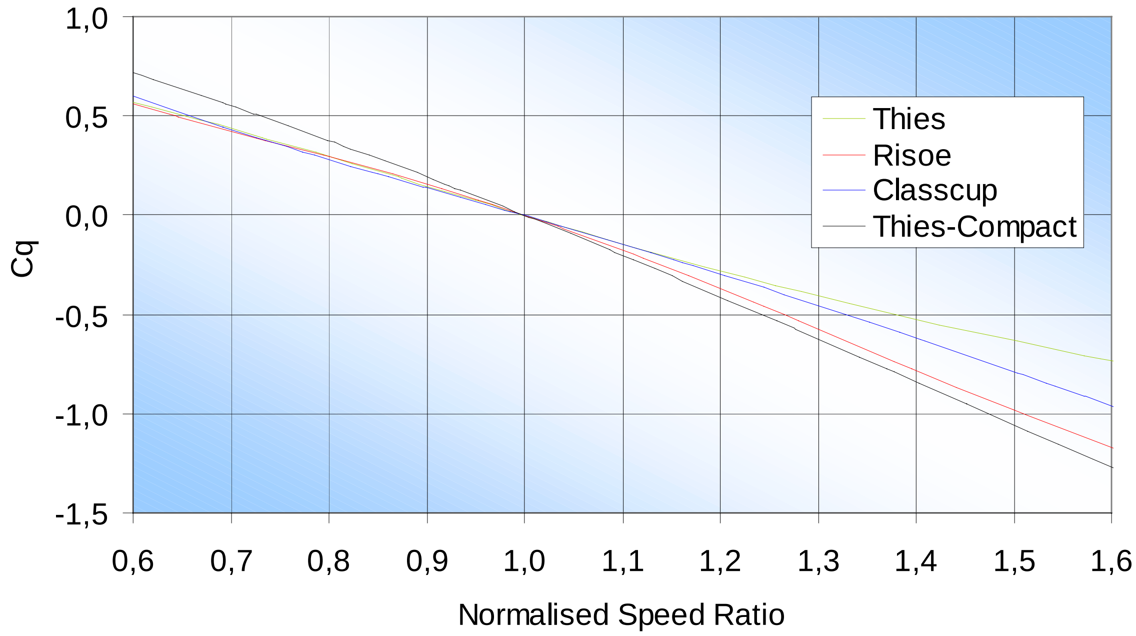

Figure 24, Normalised Torque coefficient Vs Normalised Speed Ratio

5.1.7 Wind Tunnel Studies of Overspeeding

Equipment to generate sinusoidally fluctuating wind, developed in this project, was used to assess the overspeeding characteristics of cup anemometers. A gust generator located at the wind tunnel outlet, consisting of two plates driven at different speeds by an electric motor could give gusts in the frequency range 0.25-5 Hz. Equivalent turbulence intensities could range from 10 to about 35%.

The anemometer being tested was mounted at the centre of the measurement section and on either side of it in the span-wise direction, Prandtl tubes were mounted to obtain the instantaneous wind speed. A series of tests were carried out in order to check how well the fast responding Prandtl tubes would be able to trace the wind variations. An estimated “reaction time” of 3 ms led to the conclusion that even winds with a gust frequency of 5 Hz would be tracked closely.

The rotational speed of the anemometer was measured by means of a 20 MHz clock to time the pulses from the tooth wheel of the anemometer.

Two other methods to assess the overspeeding were also used. One method was based on a direct comparison of the number of pulses from the anemometer under test and the pulses from a specially designed fast responding propeller anemometer. The other method, “Twin-Test” was based on a direct inter-comparison of the number of pulses from two anemometers mounted opposite to each other, one on the wind tunnel floor and the other in the wind tunnel ceiling. For this test Classcup bodies were used for both anemometers. The local effects was tested by inter changing the positions of the cups.

All tests show a clear picture. Some anemometers can have a high tendency to overspeed and some can even have a tendency to underspeed. Below some results are presented.

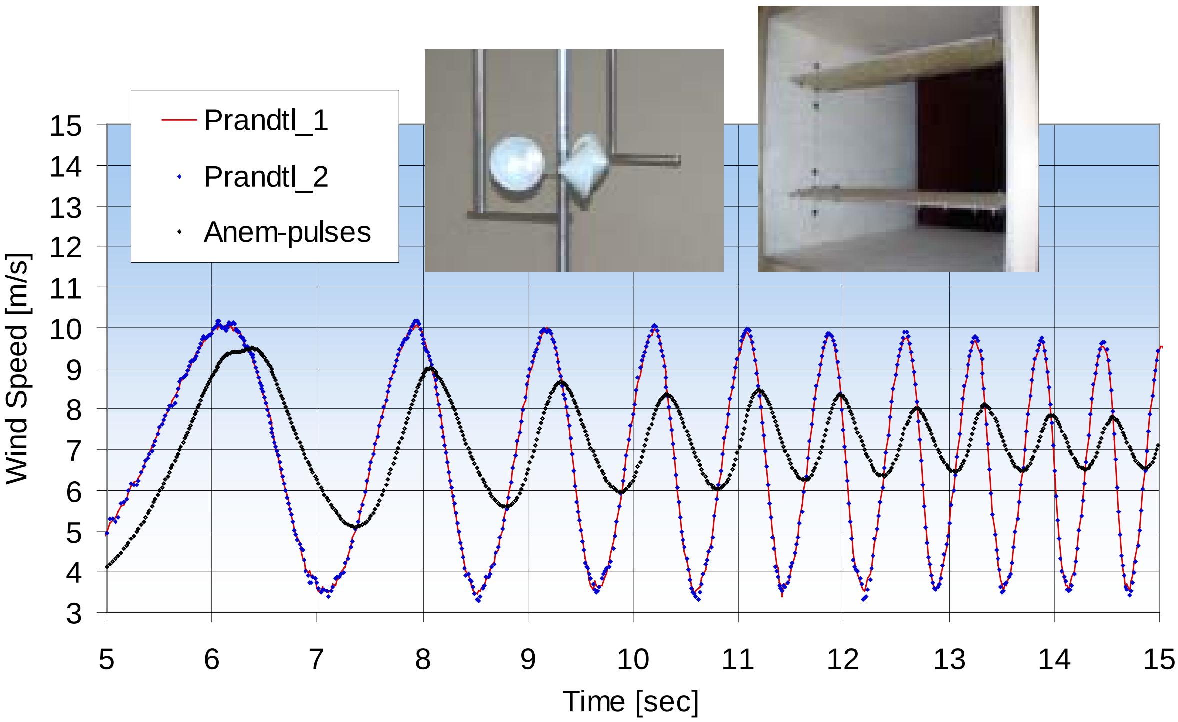

Figure 25, Example of gusts with gust frequencies ranging from 0.5 up to 2 Hz.

5.1.8 Runs with the wind gust generator and the Prandtl-tubes as wind speed reference

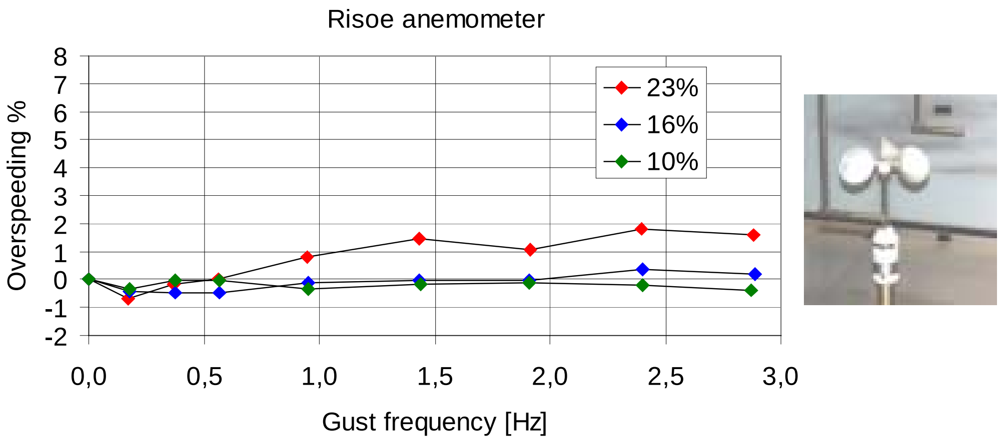

Figure 26, Gust runs with the Risoe-2445b anemometer.

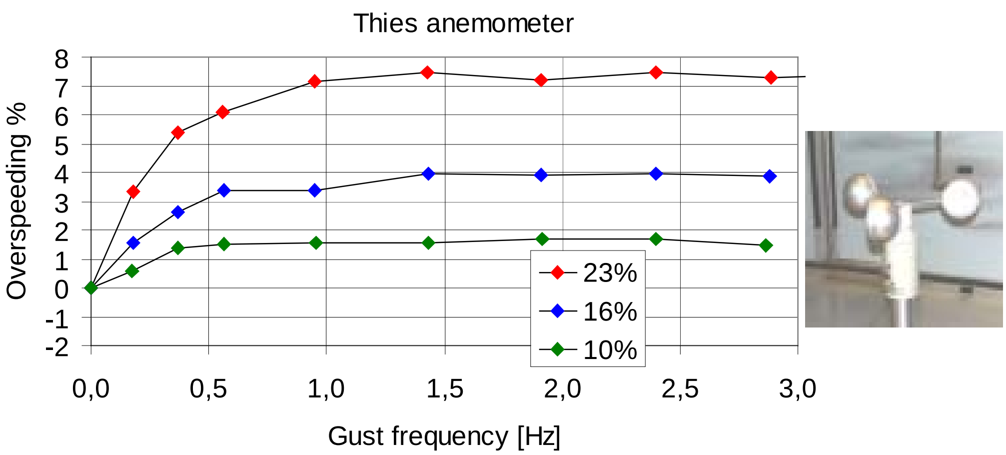

Figure 27, Gust runs with the Thies anemometer.

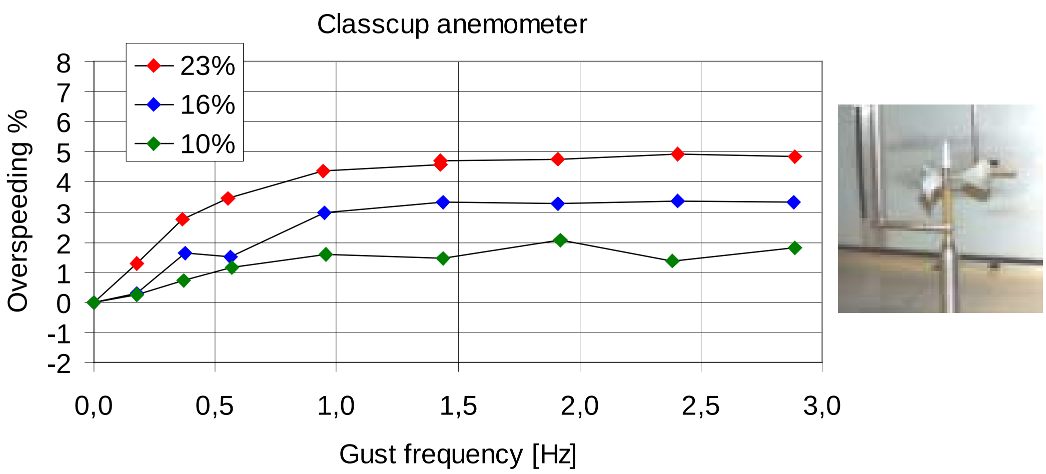

Figure 28, Gust runs with the Classcup anemometer.

Figure 29, The light weight fast responding propeller anemometer. It is believed that this device has virtually no overspeeding.

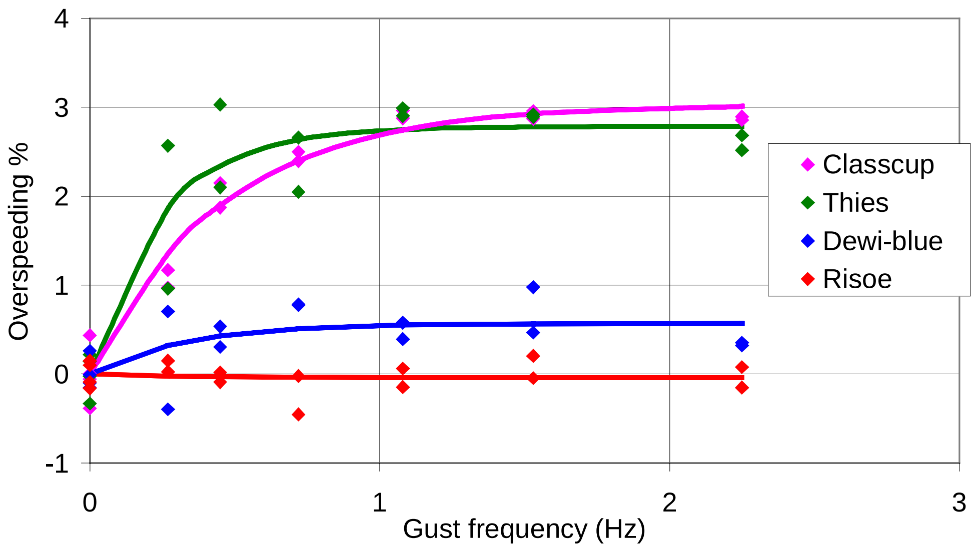

Figure 30, Overspeeding relative to the propeller anemometer at 16 % turbulence for different cups mounted on the Classcup body. The cups denoted “Dewi-blue” are an experimental design with conical cups designed by DEWI for field tests.

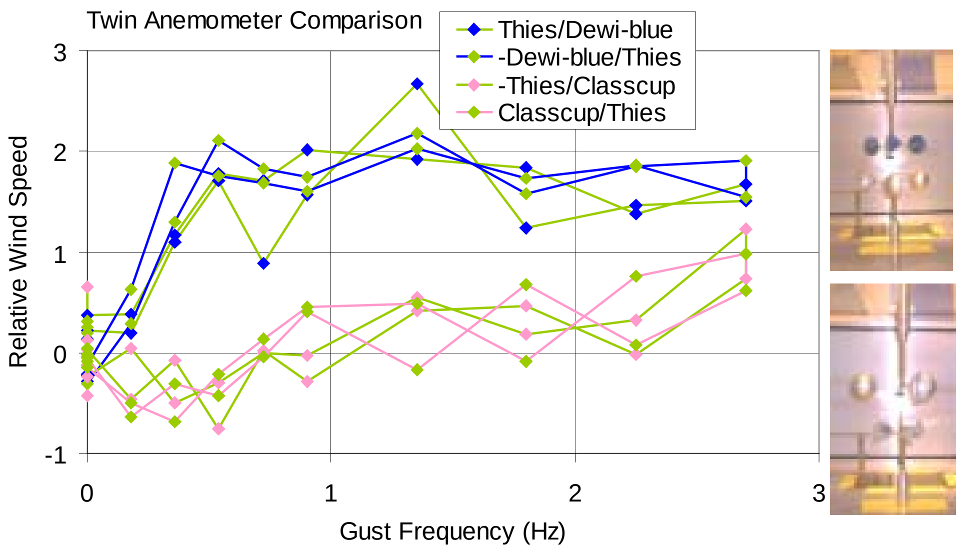

Figure 31, Twin test with Thies/Dewi-blue and Thies/Classcup anemometers

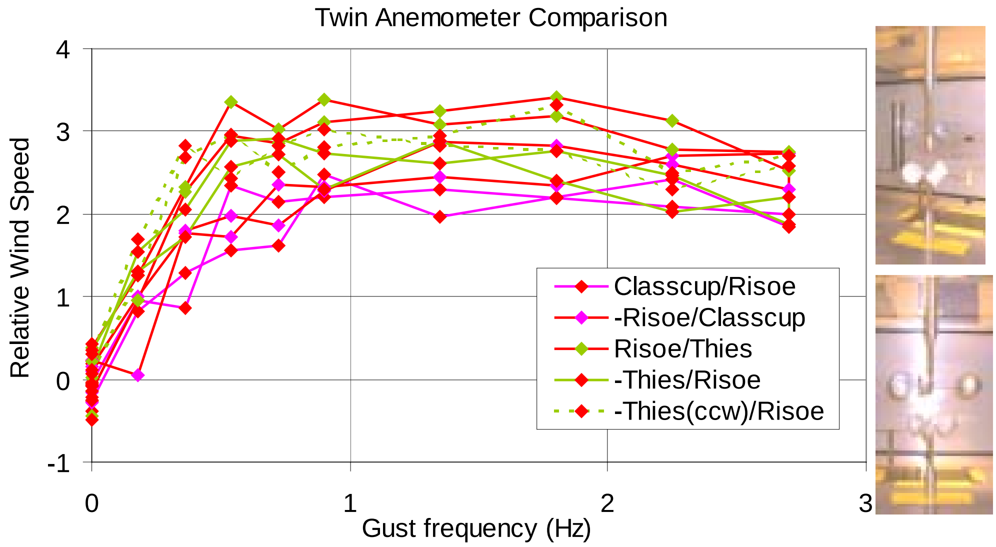

Figure 32, Twin tests with Classcup/Risoe and Risoe/Thies anemometers

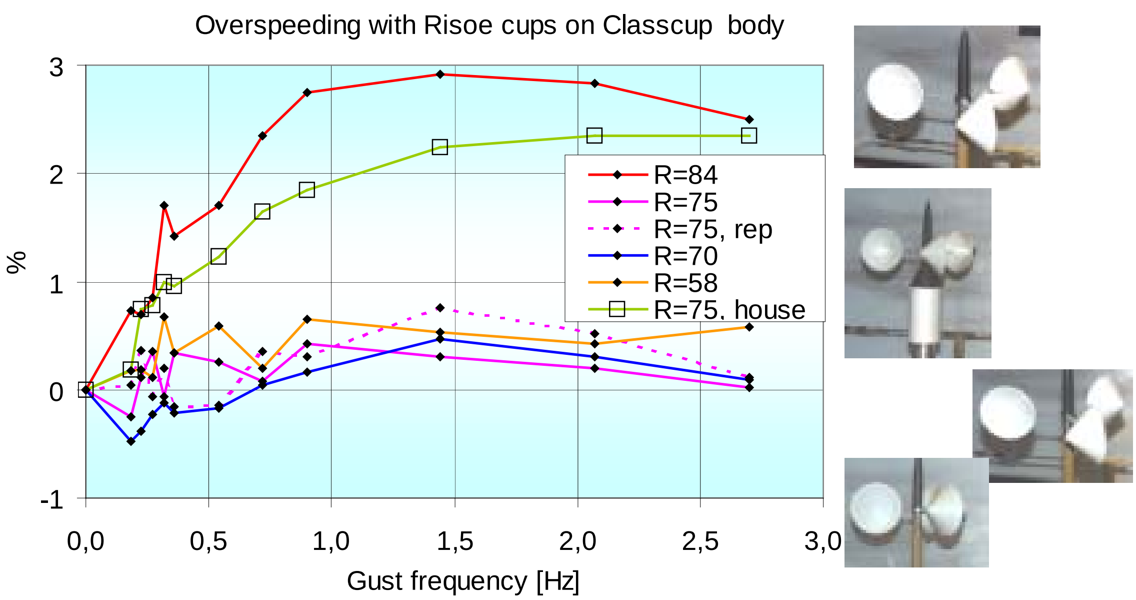

Figure 33, Overspeeding influenced by arm radius and presence of a house for Risoe cups at 16% turbulence.

<u>Conclusions from overspeeding studies</u>

The tests with different anemometers and anemometer configurations clearly show that different anemometers may have significantly different tendency to overspeed. Some observations are:

Keeping the arm-radius for the Risoe cups on the Classcup body below a certain value prevents the anemometer to overspeed.

Adding a fat body increases the overspeeding both for the Dewi-blue cups (not shown) and for the Risoe cups.

5.2 Field Studies and Verifications

Assessment whether the angular response results for steady flow conditions in the wind tunnel are consistent with those for field conditions have been carried out.

For this purpose DEWI installed an 8 m high meteorological mast in flat terrain especially designed to perform outdoor comparisons of anemometers. The cup anemometers to be tested are installed on perpendicular tubes on top of the mast. One of the cup anemometers can be tilted in definite angles in order to study systematically the influence of inclined flow.

Before starting the comparison of the tilted anemometers extensive tests were carried out to verify the homogeneity of the flow at the anemometers positions.

In the following graphs are presented to exemplify some results from the field tests:

Figure 34, 8m-Mast for outdoor comparison of cup anemometers.

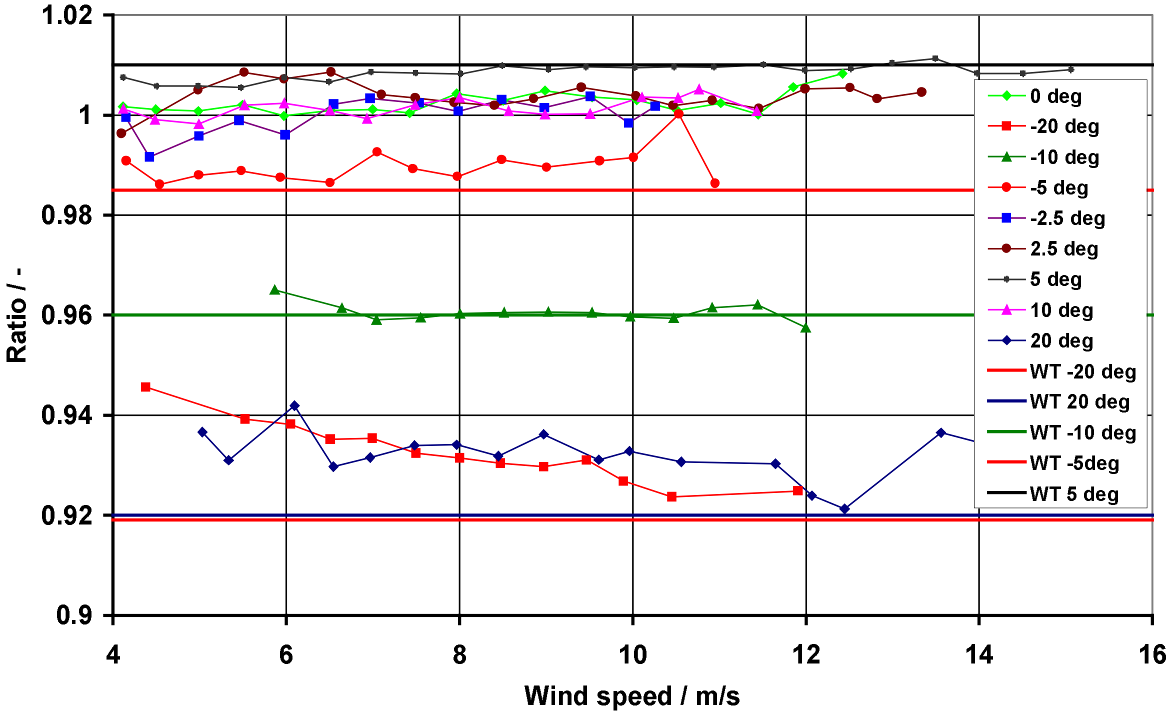

Figure 35, Ratio of tilt anemometer and reference anemometer for the Risø anemometer as a function of the wind speed for different tilt angles. Scatter line: field measurement, solid line wind tunnel results

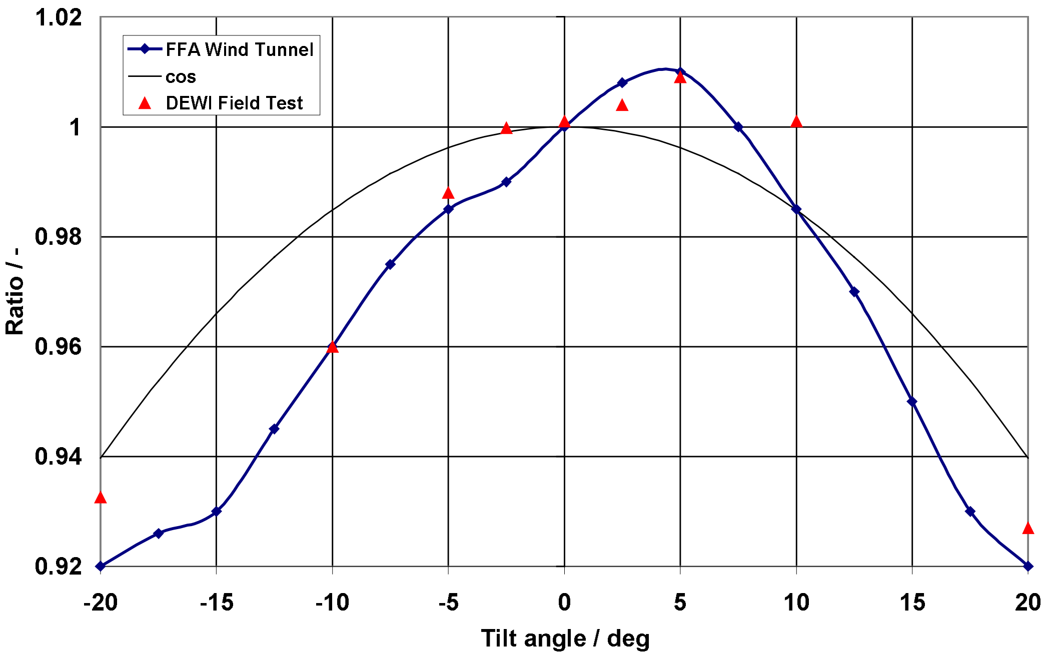

Figure 36, Comparison of wind tunnel test and field test of Risø anemometer as a function of the tilt angle. Scatter line: wind tunnel test, dots: field test

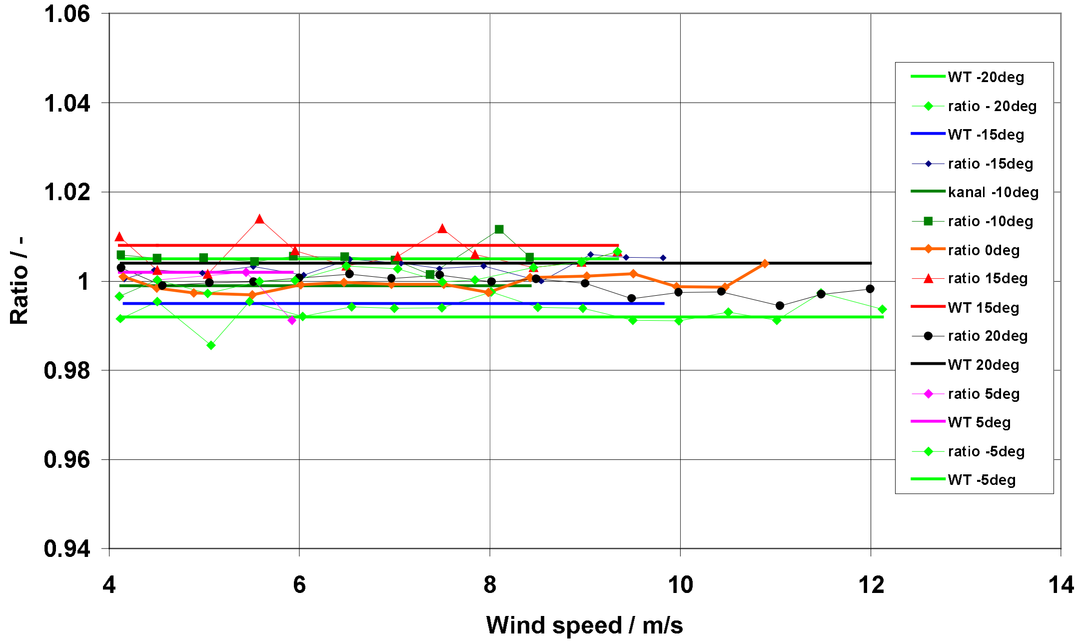

Figure 37, Ratio of tilt anemometer and reference anemometer for the CLASSCUP anemometer as a function of the wind speed for different tilt angles. Scatter line: field measurement, solid line wind tunnel results

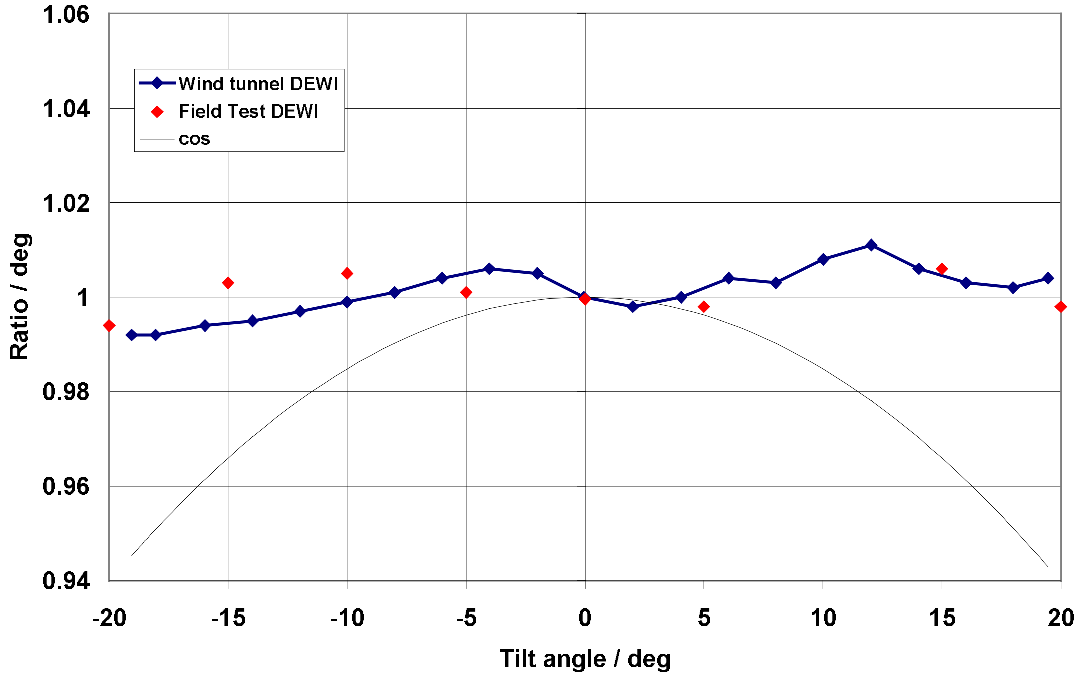

Figure 38, Comparison of wind tunnel test and field test of the CLASSCUP anemometer as a function of tilt angle. Scatter line: wind tunnel test, dots: field test

The conclusions were that the results from the field tests were consistent with those for steady flow conditions obtained from the wind tunnel tests.

5.3 Bearing Friction Effects

Cup-anemometers have rotors, and the rotors are transferring loads through the bearing systems. The design wind speeds of cup-anemometers are high so that they can resist extreme wind speeds. For this reason, the bearings are well over-designed for the most interesting wind speeds up to 20m/s, and the friction in bearings become important in relation to systematic operational errors. Therefore, the study on the bearing friction was made to support modelling of cup anemometers for the classification system.

Two procedures to determine friction in bearings were assessed. The first procedure used a set-up, where the cup-anemometer body was rotated in a fixture. This procedure did not give satisfactory results and was given up.

The second procedure was based on a flywheel method. The cup arrangement is taken off the rotor, and a flywheel, either a flat type or a compact type with same diameter to height ratio, is mounted on the shaft. The flywheel was accelerated, and the free deceleration was monitored. Considering the friction in bearings and the friction on the flywheel to bee the only forces to decelerate the rotor, the friction could be found. Below some results from the studies of bearing friction effects are presented.

Figure 39, Experimental set-up in climate chamber for cup-anemometer friction tests. The RISØ cup anemometer is mounted in the set-up with a compact flywheel. The Dana, NRG, Vaisala and Thies are shown in the background, also with compact flywheels.

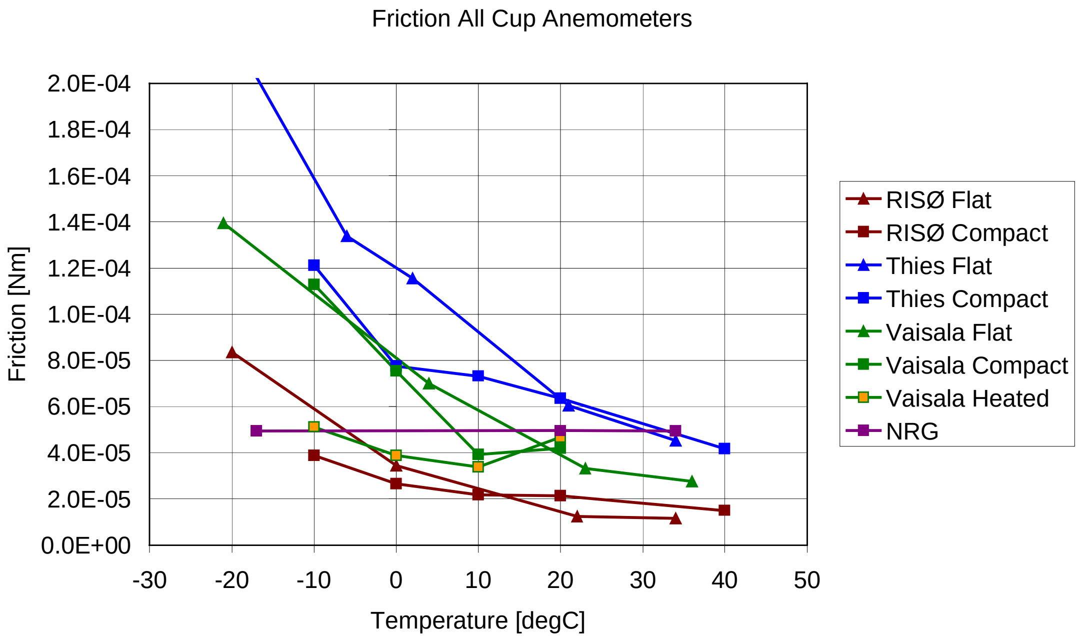

Figure 40, Friction torque at 10m/s for all friction measurements

From the measurements it was found, that the friction is satisfactory expressed by a parabola:

$$F(\omega) = f_0 + f_1\omega + f_2\omega^2$$

The influence of friction is a lowering and tilting of the calibration line, and the line is almost linear. The offset at normal calibration temperature (15-20°C) is in the order of a few cm/s, which for some anemometers was found to be only 5% of the total offset and far from the total calibration offset in the order of 20-40cm/s. In other words, the offset of the calibration line is for the main part not due to friction.

On the other hand, at low temperature below –10 to -20°C the friction increases with a factor of 3-5. The anemometer with the highest increase in friction could at -17°C get a lowering of the calibration line with 4.5-5.5% in the wind speed range 4-16m/s.

5.4 Dynamic Response Effects

Once the dynamic equations that govern the motion of the cup anemometer are known, it is possible to use this information to go the other way – from a known anemometer output signal to the unknown wind input signal that produced it. This process, called deconvolution has been investigated and reported previously and the conclusions were that the best results were obtained when the models were fitted to measured torque characteristic data. In the following example a 2:nd order polynomial has been fitted to the measured torque coefficient values. The simplified dynamic equation that governs the motion of the anemometer can be written as: $\dot{\omega} = \frac{R\rho A}{2I} * U^2 * C_q(\lambda)$. Inserting $C_T(\lambda) = a\lambda^2 + b\lambda + c$ and $\lambda = \frac{R\omega}{U}$ into the equations, the unknown wind input signal *U(t)* can be calculated from the known anemometer output signal *ω(t)* according to the expression:

$$U(t) = \frac{-B\omega - \sqrt{B^2\omega^2 - 4AC\omega^2 + 4C\dot{\omega}}}{2C}$$

The only missing quantity in the above equation is the angular acceleration $\dot{\omega}\,(t)$ which can be calculated from the measured time series of the anemometer output signal *ω(t)* as central differences according to: $\dot{\omega}_i = \sum_{j=1}^{n} C_i(\omega_{i+j} - \omega_{i-j})/(t_{i+j} - t_{i-j1})$

The values of C_i were searched by a fitting procedure where the difference between the wind speed measured by the Pandtl tubes and the deconvoluted wind speed was minimised. The graphs below show some results:

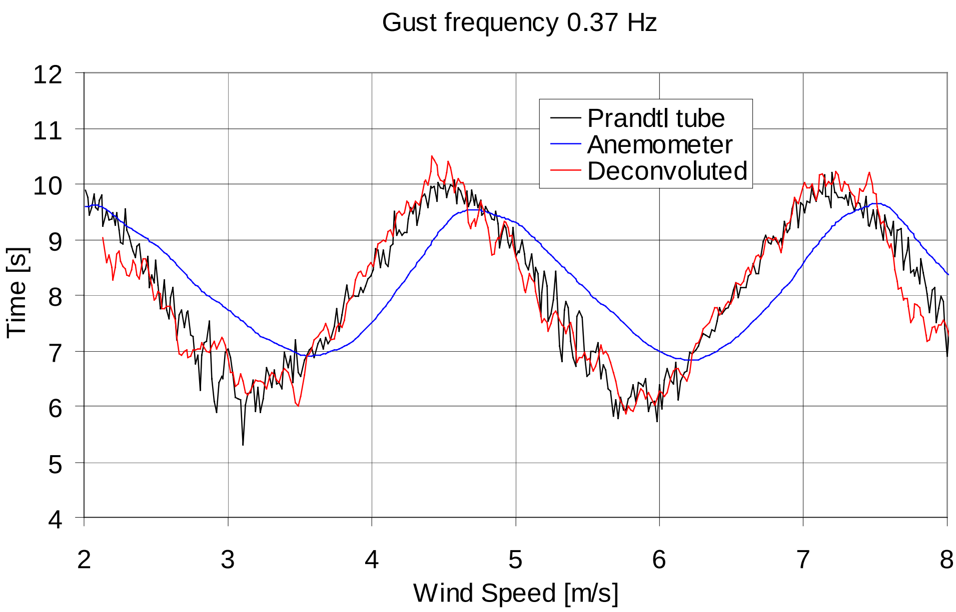

Figure 41, Part of time series with fluctuations at 0.37 Hz.

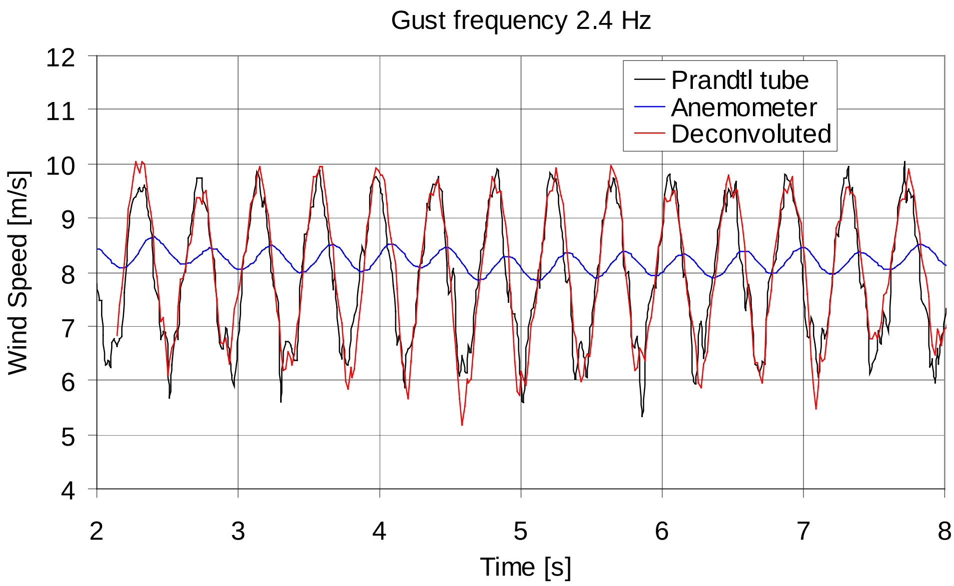

Figure 42, Part of time series with fluctuations at 2.4 Hz.

The table below shows the results when the optimisation was set to minimise both the overspeeding and the tracking error for high-frequency gusts

	Optimised to Minimise Wind Speed Error				
Run->	5 m/s	8 m/s	11 m/s	0,37 Hz	2,4 Hz
	Prandtl Tubes/Wind Tunnel Speed				
"True Wind Speed"	5,14	7,95	10,98	8,08	7,99
"True Turbulence" %	1,8	1,2	1,3	16,2	15,0
	Anemometer				
Wind Speed	5,13	7,97	10,94	8,24	8,24
Error/Overspeeding %	-0,1	0,2	-0,3	1,9	3,1
Turbulence %	1,0	1,2	1,0	11,6	2,2
	Deconvoluted				
Wind Speed	5,17	7,97	10,89	8,12	8,06
Error/Overspeeding %	0,6	0,2	-0,8	0,4	0,9
Turbulence %	3,0	3,1	3,1	17,1	15,6

5.5 Conclusions

The example shows that deconvolution greatly enhance the performance of the anemometer during wind gusts and significantly reduce the overspeeding error. An even better deconvolution is possible if the optimisation is set to minimise either the overspeeding or the traceability for high-frequency gusts.

5.6 Development of a Classification System

A classification method for cup anemometers has been proposed. General external operational ranges have been proposed based on a wind speed range, a turbulence range, a length scale range, an air temperature range, an air density range and a slope of flow range. A normal category range connected to ideal sites of the IEC power performance standard was made, and another extended category range for complex terrain was proposed. General classification indices were proposed for all types of cup anemometers.

At least four cup anemometers models have been analysed. In the end the Cq table interpolation model seemed to give the best results. This model was then used to simulate characteristics of four cup anemometers at the outer limits of the operational ranges. The results are classifications of the four anemometers for normal and extended categories and for horizontal and vector measurements.

As a result of the classification, the cup anemometer will be assigned to a certain class: 0.5, 1, 2, 3 or 5 with associated intrinsic errors of ±0.5%, ±1%, ±2%, ±3% or ±5% as a vector instrument (3D) or as a horizontal instrument (2D) for a normal and an extended category of operational ranges.

In the following some results from the development are highlighted:

The following tables show the operational ranges of the proposed classification categories.

5.6.1 Normal Range (Typical operational ranges for wind turbine power performance measurements at ideal sites)

Parameter	Normal range		
	Min	Ave	Max
Wsp (10min) [m/s]	4	4-16	16
Turb.int.	0.03	0.10	0.12+0.48/V
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$.	1/0.8/0.5		
Length scale L_k [m]	100	500	2000
Air temp. [°C]	0	10	40
Air density [kg/m^3]	0.9	1.23	1.35
Slope [°]	-5	0	5
Ice, snow, rime conditions	not included		

5.6.2 Extended Range

(Typical operational ranges for wind turbine power performance verification measurements including complex terrain)

Parameter	Extended range		
	Min	Ave	Max
Wsp (10min) [m/s]	4	4-16	16
Turb.int.	0.03	0.10	0.12+1.13/V
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$.	1/1/1		
Length scale L_k [m]	100	500	2000
Air temp. [°C]	-10	10	40
Air density [kg/m^3]	0.9	1.23	1.35
Slope [°]	-15	0	15
Ice, snow, rime conditions	excluded		

5.6.3 Some results from the classification:

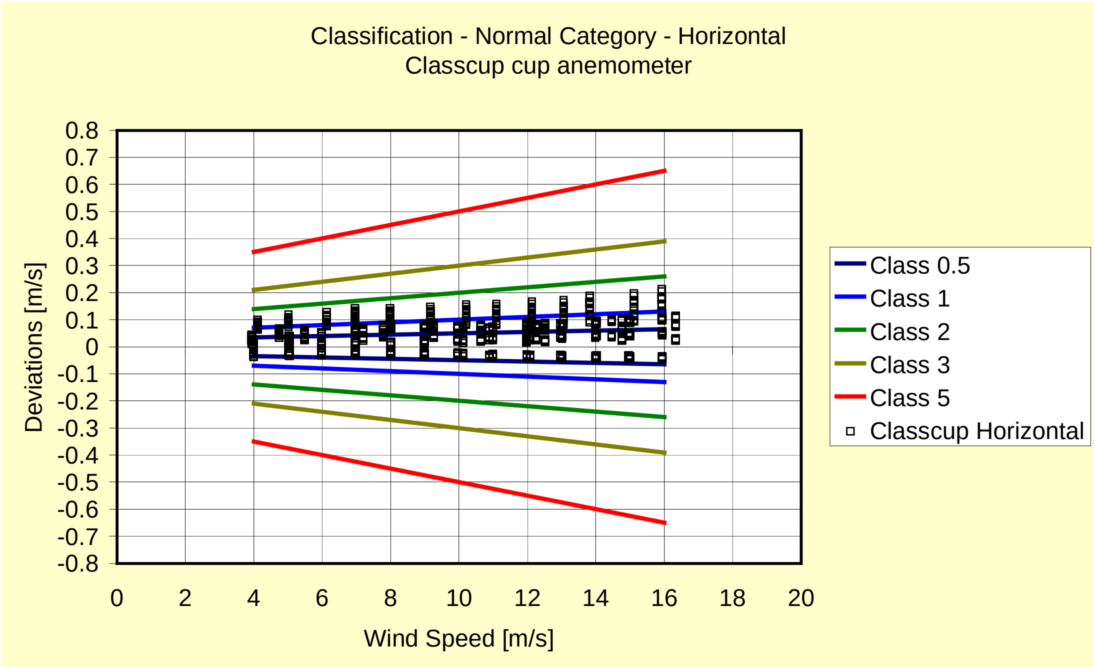

Figure 43, Classification of the Classcup anemometer as a horisontal anemometer under normal conditions.

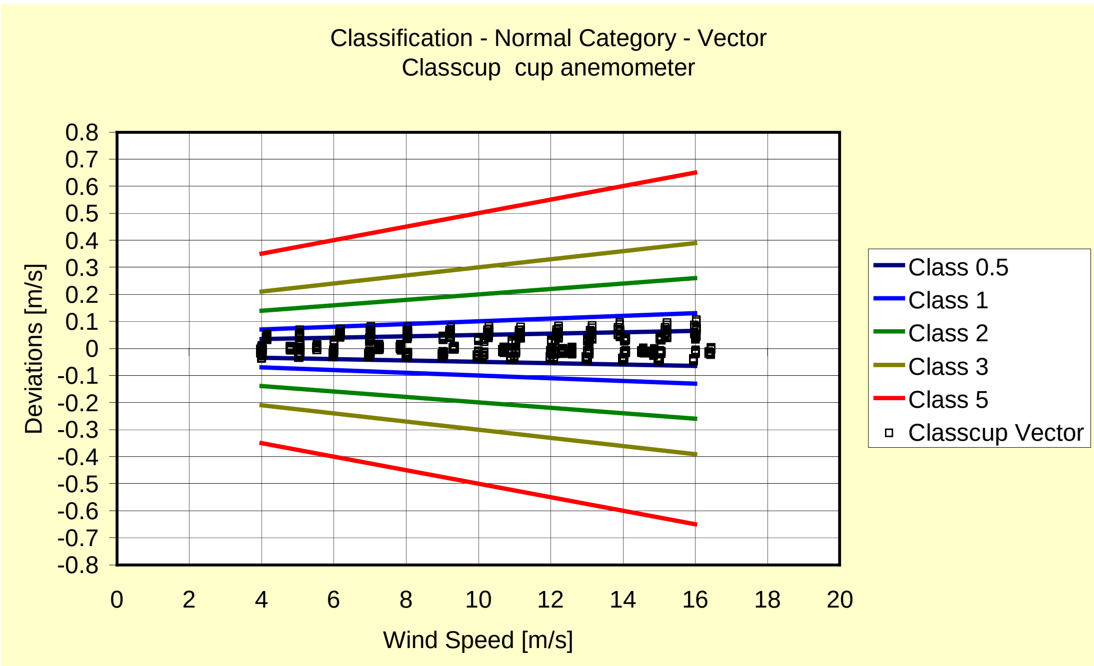

Figure 44, Classification of the Classcup anemometer as a vector anemometer under normal conditions.

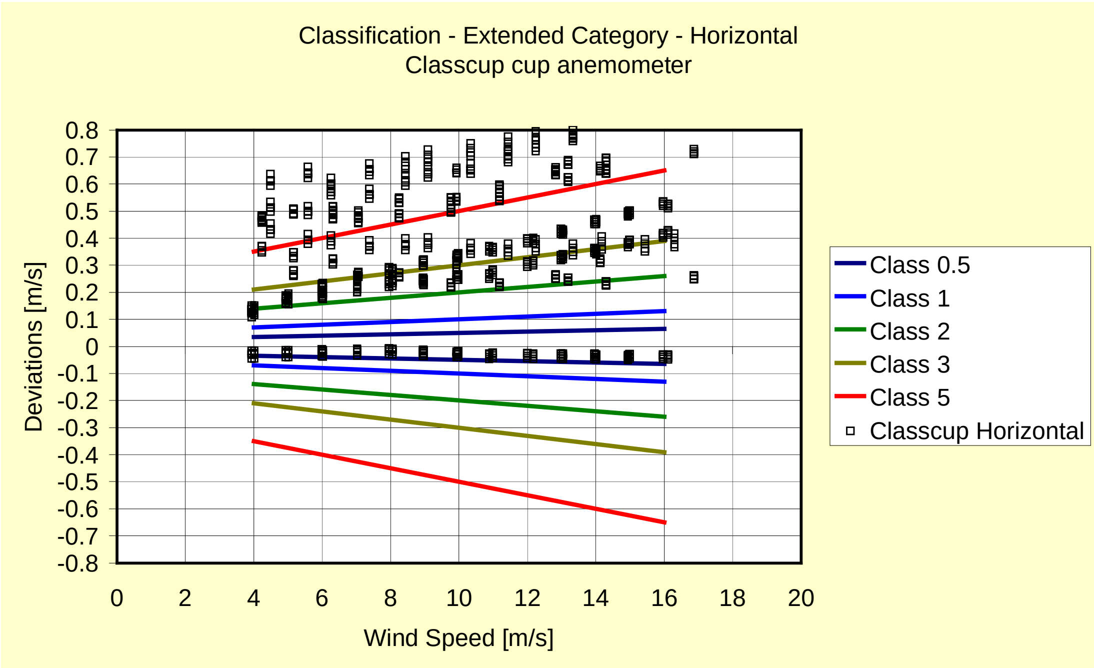

Figure 45, Classification of the Classcup anemometer as a horisontal anemometer under extended conditions.

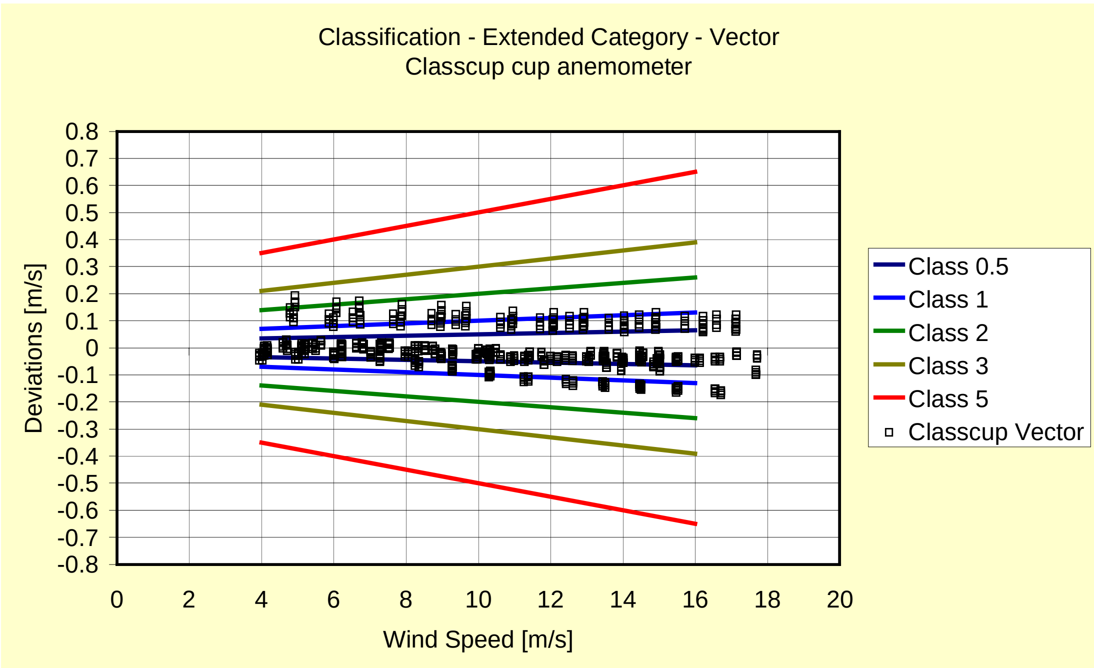

Figure 46, Classification of the Classcup anemometer as a vector anemometer under extended conditions.

The summary of the classification is shown in the following table.

Cup anemometer	Normal Category Horizontal	Normal Category Vector	Extended Category Horizontal	Extended Category Vector
RISØ	2	3	5	-
Thies	3	3	-	5
Thies Compact	5	5	-	-
Classcup	2	1	-	3

The classification of the three commercial cup anemometers showed that for the normal category the best class for horizontal wind speed measurements was class 2 and for vector measurements class 3. The Classcup prototype anemometer got a class 1 as a vector anemometer and class 2 as a horizontal anemometer. For the extended category the commercial cup anemometers were class 5 for either horizontal or vector measurements, whereas the Classcup anemometer got a class 3 as a vector instrument.

By using the Classcup anemometer the accuracy of vector wind speed measurements has therefore significantly improved. However the improvements did not meet the original targets. The improvements of the angular response met all ambitions, but the influence from overspeeding turned out to be more significant than expected. For the Classcup anemometer the overspeeding is the reason for not being assigned to a better class.

The deconvolution method, that was developed in the project and verified as being able to reduce overspeeding effects substantially, could potentially improve the classification of the Classcup anemometer and it could also potentially improve the class of other commercial cup anemometers, prone to overspeeding.

6 Results and Conclusions

The extensive experiments from tests in wind tunnels, of more than 500 anemometer configurations, fields tests and tests in laboratories together with the assessment and modelling work have helped to build up an understanding of the importance of different design parameters in terms of various behavioural effects.

A decision was made to focus on conical cups since their sensitivity to vertical velocity components appeared to be less sensitive to the wind speed. This decision turned out to be successful in that modifications of the shape of conical cups turned out to be a possible road to the development of an angle-insensitive anemometer. The conical cup shapes were also found to be favourable in terms of overspeeding.

The key measures taken to develop the new design were an appropriate selection of the detailed design of the cups and mount the cups at appropriate radius on a slender symmetric body. The development finally ended with an anemometer that gave a very good flat response within 1% over the inflow angle range from –45º to +35º and had good linear calibration curve.

The inflow angle response was also tested in the field, by which two anemometers were tested side by side on top of a 8m high mast. The anemometer under test was mounted in fixed tilted positions and compared with the vertically mounted reference anemometer. The flat response tests, found from wind tunnel with the Classcup anemometer, were confirmed by field tests over the range ±20°.

A patent application was filed to the Swedish Patent and Registration Office on the 6:th of October 2000.

A near-cosine response curve was achieved with conical Risø cups placed at appropriate radius and with the cup opening covered by discs.

The overspeeding of different cup anemometers have been examined experimentally using a wind gust generator. The extensive experiments have shown that anemometers of different design can have very different tendency to overspeed. The tests performed in different ways show all a clear picture. Some anemometers can have a high tendency to overspeed and some can even have a tendency to underspeed. This has never been so clearly shown before.

The Classcup anemometer optimised for flat angular response proved to have a relatively high tendency to overspeed.

Some general conclusions from the parametric studies of overpeeding were:

Conical cups on a relative small arm radius and a slender neck gave negative to low overspeeding. Increasing the radius above a certain value or adding a fat body brought the overspeeding up.

Measurements of dynamic driving torque from complete rotors were carried out for different anemometer configurations. When the measured torque were normalised with dynamic pressure, cup area and arm radius the torque characteristics versus speed ratio $C_q(\lambda)$ could be determined. The torque measurements were used to calculate the dynamic response of the cup anemometer, i.e. the torque acting on it to get it back to equilibrium conditions, when it is slightly accelerated or decelerated by a wind gust.

Calculations of overspeeding, based on the measured torque characteristics, have shown how vital not only the general trend but also the very detailed shape of the torque characteristics are, for the performance of cup anemometers operating in turbulent conditions.

The studies have shown that calculations of overspeeding agree well with the measured overspeeding as long as all details in the measured torque characteristics were used.

Attempts to calculate the overspeeding from models based on static drag data for the cups and other geometric data, as has been used previously have shown to give erroneous results. These models can not predict underspeeding.

The results from the comparative field measurements with different commercial cup anemometers can qualitatively be explained by either mainly angular response effects or mainly dynamic response effects or by combinations of the two effects.

The method of deconvolution, i.e. try to extract the input wind signal that gives the acquired output signal from the anemometer, has been examined. A model was derived from the measured torque characteristics for the Risoe and the Classcup anemometers. The results were promising – the deconvolution seems to greatly enhance the tracing ability of the anemometer and significantly reduces the overspeeding error.

Bearing friction was found to have an influence, but only a significant influence at low temperatures. The influence of friction is an offset and a tilting of the calibration line. The combined influence of the friction is a lowering and tilting of the calibration line, and the line is almost linear.

The best way to measure the friction is by a flywheel test. Two types of flywheels were tested, a compact type and a flat type. The compact type has the advantage that air friction is insignificant, but a disadvantage is, that at low temperatures, the deceleration is too fast. The flat type has the advantage that the deceleration lasts longer, but the air friction should be taken into account.

A classification method for cup anemometers has been proposed. General external operational ranges have been proposed based on a wind speed range, a turbulence range, length scale range, air temperature range, air density range, slope of flow range, and turbulence structure has been defined. A normal category range connected to ideal sites of the IEC power performance standard was made, and another extended category range for complex terrain was proposed. General classification indices were proposed for all types of cup anemometers.

Four cup anemometer models have been analysed. In the end the Cq table interpolation model seemed to give the best results. This model was then used to simulate characteristics of four cup anemometers at the outer limits of the operational ranges. The results are classifications of the four anemometers for normal and extended categories and for horizontal and vector measurements. As a result of the classification, the cup anemometer will be assigned to a certain class: 0.5, 1, 2, 3 or 5 with associated intrinsic errors of ±0.5%, ±1%, ±2%, ±3% or ±5% as a vector instrument (3D) or as a horizontal instrument (2D) for a normal and an extended category of operational ranges.

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The deconvolution method, that was developed in the project and verified as being able to reduce overspeeding effects substantially, could potentially improve the classification of the Classcup anemometer and it could also potentially improve the class of other commercial cup anemometers, prone to overspeeding.

7 Exploitation Plans

Exploitation plans are:

- to offer the design to European manufacturers on a non-exclusive licensing arrangement.
- to promote adoption of the new anemometer by all members of the MEASNET grouping.
- to encourage general adoption of the new design and the new classification system within the wider wind energy community through technical papers and publications.
- to offer access to our knowledge and facilities to a wider wind energy community on consultancy basis.

8 Symbols/Abbreviations

2D	two dimensional
3D	three dimensional
“α-sweep”	turning the turntable slowly with the anemometer on a pole in the centre of the tunnel
“β-sweep”	moving the tilt device slowly back and forth in the centre of the tunnel
λ	speed ratio = $R*\omega/U$
ρ	air density
σ_k	velocity component standard deviation
ω	angular speed
C_q, C_T	torque coefficient
F	friction torque
f_i	polynomial coefficients in friction expression
I	inertia
inflow angle	the angle between the wind vector and the horizontal plane. Negative angles (and above 90° in some graphs) means wind from below.
L_k	velocity component integral scale parameter (length scale)
overspeeding	relative difference between the rotational speed for actual conditions and stationary conditions
rel. speed, ratio	the rotational speed at a given inflow angle divided by the rotational speed at zero inflow angle
R	cup radius, distance from centre of rotational shaft to the centre of the cup
R	radius
U, V	wind speed
u, v, w	longitudinal, lateral and vertical velocity component